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ON
NUCLEAR
ENERGY

ON NUCLEAR ENERGY

ITS POTENTIAL FOR PEACETIME USES

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With a Foreword by LEWIS L. STRAUSS
Chairman, Atomic Energy Commission

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TO MOTHER

This one is for you — it
contains only two equations.

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PREFACE

This volume is a direct outgrowth of many lectures that I have given on peacetime nuclear energy since the subject first became front-page news in 1945. In the dozen years that have now elapsed, the intense public interest has continued unabated, and rightly so. The wartime development was paid for completely by public funds, as has been most of the postwar program; hence the citizens in actuality own most of the nuclear energy business in the United States—a two-billion-dollar-a-year business.

In giving lectures to a wide variety of lay groups, I have always been impressed with the real eagerness of the listeners to learn something of nuclear energy, and their willingness to put in a few hours of concentrated effort in the process. The desire was not so much to be told astounding predictions of the future as to learn the solid facts of atomic structure, fission, the chain reaction, and the many applications of nuclear energy that are possible right now. Further, it was always gratifying that the listeners, with no technical training but with a keen desire to learn, could gain a real understanding of the basic principles in a short time.

It was often suggested that the material of these lectures, if written down, might find a wider audience and serve to increase the understanding of atomic facts. Thus when Harvard University Press proposed a book on nuclear energy that would be authoritative and emphasize the peaceful aspects, I most willingly agreed. This volume thus represents the material developed in these dozen years of lectures, written as much as possible in the manner in which is was successful in presenting the fundamentals accurately, yet simply. It is not a digest of many written reports but practically completely represents my own direct knowledge of the field, which has occupied me fully since 1942, when the first chain reaction was attained.

This preface is being written under somewhat unusual circumstances—on my trip homeward from a month spent behind the Iron Curtain. Having finished two weeks of lecturing in Poland and another two in the Soviet Union at the invitation of their Academies of Science, I have had an excellent chance of learning more about the international atom. Relations at present on the scientific level continue to improve between East and West; while I was in Warsaw, Kraców, Moscow, and Leningrad, it was possible to discuss progress and plans without restraint. The Soviet scientists are looking forward eagerly to presenting their results at a conference to be held this autumn at Columbia University and to renewing their contacts with us at the second Geneva meeting in 1958. It was of great satisfaction to learn that my optimistic hopes expressed in Chapter 7 concerning international coöperation are in no way decreased by this visit but are actually strengthened somewhat. And the prediction voiced in the last sentence of the book already seems to be near realization, for the Soviet scientists discussed eagerly how at Geneva II there would be extensive sessions on research concerning thermonuclear reactions.

The writing of this book has been aided greatly by the advice of J. D. Elder, Science Editor of Harvard University Press, and by many friends who have read the manuscript. R. C. Garth has been of great assistance in many phases of the writing, as has Mrs. A. Marshall in typing the manuscript and G. Cox in preparing the figures. Many of the illustrations have been supplied by the Publication Department of Brookhaven National Laboratory. I wish to record my heartfelt thanks for all this aid; the book would have been impossible without it.

D. J. Hughes

Aboard *Cristoforo Colombo*
July 22, 1957

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FOREWORD

Dr. Donald J. Hughes of the Brookhaven National Laboratory is one of that group of gifted scientists who assisted at the advent of the nuclear age in the United States. He worked first during World War II on the secret military development of atomic energy and since the coming of peace has devoted his talents to basic scientific inquiry into the laws which govern the atom and its component particles. He is particularly qualified therefore, because of his intimate knowledge and long association with nuclear science, to write this book. The result is a volume comprehensive in scope and engrossing in treatment. The fundamental facts of nuclear fission and fusion, the chain reaction, the production of power from nuclear fuels, and the many and growing uses of radioisotopes are discussed by Dr. Hughes in nontechnical terms, with precision and clarity. His summary of the atomic-energy programs of the various nations is one of the most complete and responsible surveys of the subject to appear in print. Dr. Hughes also writes with insight about such vital developments as President Eisenhower's inspired program of Atoms for Peace and the International Atomic Energy Agency which is a first fruit of the President's bold vision. To readers anxious to learn more about the promises and the problems of a new art which already touches the lives of us all this book will provide a rewarding experience.

LEWIS L. STRAUSS

ON
NUCLEAR
ENERGY

CHAPTER 1

NUCLEAR ENERGY FOR WAR AND PEACE

And atomic energy, unless we ban it,
Will blow us right off this old planet.
—ANONYMOUS (1945)

The world was dramatically made aware of the energy contained in the atomic nucleus by the explosions over Hiroshima and Nagasaki in early August 1945. However, only the destructive phase of the unleashing of nuclear forces was evidenced by these two bombs, each the equivalent of many thousands of tons of high explosive. Here was a new weapon of power hitherto undreamed of by man, whose widespread use could wreak destruction almost impossible to comprehend. Thus at the end of the war a few days later, which was hastened by this new weapon, the immediate reaction was to find some method, however desperate, for avoiding atomic warfare.

Many proposals soon followed the shock of Hiroshima and Nagasaki for curbing the atom's power for harm. Although many of these may now appear extremely unrealistic, their sources are easy to understand in terms of the temper of those times. The energy hitherto locked in the nuclei of atoms had been released only for evil, and a few pounds of material would suffice to cause the death of a hundred thousand human beings. Nothing was publicly known as yet of the atom's power for good—the production of electricity and of radioisotopes. Hence the old suggestions that physical sciences, having advanced beyond our social structure, should be retarded, were again heard. It was seriously proposed that investigations of the applications of nuclear fission should be forbidden, or that scientists by agreement should cease work in this field.

Before long, however—actually in a matter of weeks—it became clear that the situation was not simply one of blotting out an unmitigated evil. Tremendous as was the destructive power of the atom, its potentialities for peace were even greater, as soon became common knowledge. In fact, a position practically the opposite of that aroused by the initial bomb news was soon produced, as the somewhat bewildered public was deluged with uncritical predictions of the complete atomic horn of plenty. In order to balance these two extreme views, the good and the evil of nuclear energy, let us examine briefly the happenings in the atomic field before the first bomb explosion.

Prospects for Peacetime Nuclear Energy before Hiroshima

The work that had proceeded through the war at the secret atomic laboratories at Argonne, Oak Ridge, and Los Alamos had as its prime objective the successful attainment of the bomb. However, it gradually became clear to the scientists concerned that the power for peace of the atom went far beyond its stark destructiveness. Early in 1945 it seemed that we would in all probability have a successful bomb that coming summer and with it peace. There was then time to reflect on the broader issues. Organized discussions took place among those scientists familiar with all phases of the project on the vast, complicated question of the correct handling of the new force when the war should end. From the limited amount of effort already devoted to the constructive aspects of nuclear energy, it was safe to conclude that the prospects were great indeed. This limited effort had not been an end in itself but, as we shall shortly learn, was inseparable from bomb development.

The investigations, although greatly circumscribed, had shown that in all likelihood uranium could serve as a source of electric power that would some day compete with oil and coal. It would be a fuel that would occupy essentially no space and produce electricity cleanly, with no smoke, and eventually almost certainly more cheaply than coal or oil. It was obvious from experiments already performed on a small scale that the by-products of nuclear energy, the radioactive atoms, or *radioisotopes,* could be used for treatment of disease and as *tracers* in countless research and industrial applications. The radiations from those atoms could change living germ cells, that is, cause *mutations,* and thus perhaps speed up evolution, producing new strains of plant and animal life.

The situation of the scientists discussing in secret these far-reaching possibilities and the correct procedure for their attainment was dramatic in the extreme. Only a few men knew of the large-scale release of the energy of the nucleus, of the almost certain success of its use as a weapon of supreme power, and of its even greater potential uses for peace. During this period I was a member of the Committee on Social and Political Implications, under the chairmanship of Professor James Franck, which met at the Metallurgical Laboratory, actually the atomic-energy laboratory in Chicago, during the spring of 1945. This committee had been given the responsibility of recommending the proper course that might serve to achieve the benefits of atomic energy for mankind.

With the atomic-energy industry now blossoming throughout the world it seems a bit strange that we worried in those days the way we did. However, I remember with great clarity that one of our main concerns was that atomic energy might not be developed at all after the war. We knew that a lot of money was involved in the wartime effort and we feared that, if the possibilities were not made abundantly clear to the public, perhaps a postwar economy drive would stop the atomic program completely. We felt that we as scientists knew the great benefits that could come from atomic energy if developed, but were afraid that the possibility of these benefits, perhaps far in the future, might not be realized by Congress and the public. Thus we were anxious for a convincing demonstration of the potency of the forces within the atomic nucleus but did not want it made effective by a wholesale destruction of human life. Our conclusion was that the bomb should be exploded, to demonstrate to the world the power of the atom, and to use this power to end the war. However, we recommended that the bomb be exploded not on a living target, but rather as an arranged demonstration on an island waste. In this way, we felt, the Japanese would be induced to surrender, and the resulting world-wide knowledge of atomic power would ensure that it would not be forgotten.

This is not the place to weigh the complicated arguments that ensued, leading to the final decision to use bombs on Japanese military targets. These have been reviewed many times since those early days and agreement has still not been reached. While the necessity of using a bomb on an actual target to convince an entire population can hardly be denied, there are many who still believe that we suffered a grievous permanent loss on a moral plane by the actual use of the bomb on Hiroshima and Nagasaki. However, there was no question of the public knowledge of atomic energy, and there was no concern that lack of interest would lead to a neglect of atomic developments. Perhaps we were too modest in those early discussions, for it now hardly seems possible that the development would have been stopped had there been no explosion of the bomb. The entire program might have moved more slowly without the military incentive, but there certainly would have been less emphasis on the weapons applications. The actual course of events before Hiroshima, however, determined that the entire field of fission applications has since been strongly affected by military applications.

The Dual Roles of Atomic Energy

As information rapidly became available on the manifold possible applications of the controlled release of atomic energy, it was obvious that no simple solution, such as the "banning" mentioned in the doggerel quoted above, was sensible. The discussions then took a somewhat different but still over-simplified approach. The burning subject then was: "Atomic energy for war *or* peace?" During the fall and winter of 1945–46, when atomic scientists were in the glamorous position of being sought as public speakers and even urged to run for public office, they were somehow expected to answer this question. I recall that often I was expected to tell how, having brought atomic fire to earth, we scientists were going to arrange things so that mankind was warmed but not burned, by its use.

Means were sought, by scientists and nonscientists alike, that would completely prevent the use of atomic energy for destruction but accelerate its beneficial applications. Had international politics been different in 1945, perhaps the separation of the good from the bad could have been made. The important point, though, is that the separation of good from bad is a matter of the *use* to which we put atomic energy, not its basic physical nature. As we shall see, bombs cannot simply be banned, for by doing so effectively we prevent development of industrial power stations. The concept of atomic energy for war *or* peace is so oversimplified that courses of action based on it are likely to be of little value.

The true picture of the destructive and constructive aspects of atomic energy is one in which the two are so interwoven that it is impossible to control one strongly without greatly modifying the other. Much of the basic reasoning leading to this conclusion must await the discussion of the fundamental facts of atomic energy that occupies most of this book. However, at present we can indicate some of the relations between the peacetime and wartime applications, without resorting to nuclear physics. While not completely convincing, the indication will nevertheless be a first step and will at least serve to show why a soundly based view of atomic energy, for peace and war, can be fully gained only after some study of its basic principles.

At the present time in the United States an enormous activity is under way in atomic energy for war *and* peace. Atomic energy is big business right now. The budget of the Atomic Energy Commission alone comes to about $2 billion annually, and to this figure must be added hundreds of millions spent yearly by industry in its privately financed atomic developments. The government investment alone in atomic energy is about $10 billion, with an additional (classified) amount of money representing our stock of bomb materials. The rapid growth in annual operating expense and plant investment of the Atomic Energy Commission during the years, shown graphically in Fig. 1, certainly gives little evidence of leveling off as yet. The magnitude of the investment in atomic energy is perhaps made even more striking when we realize that every family in the United States now owns on the average something like $300 worth of the government atomic-energy business. Thus each individual can rightly feel that it is *his* business: he certainly has a right to know how it is related to war and peace and, as well, a duty to understand how to direct the business intelligently.

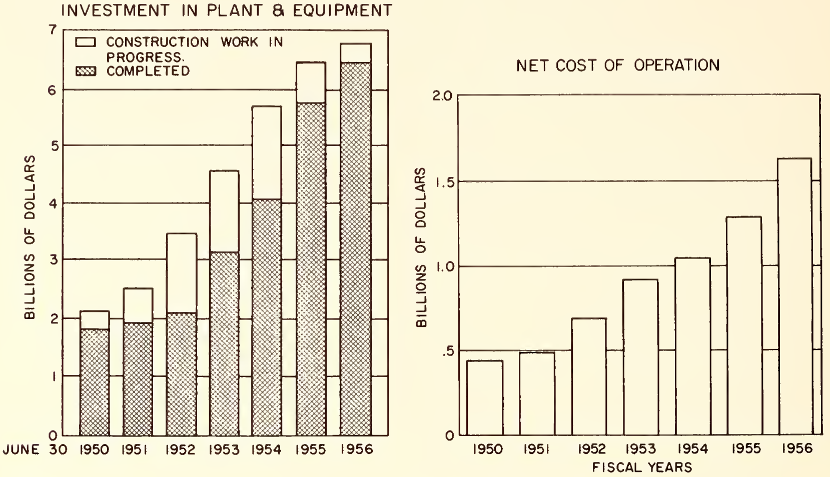


Fig. 1. The annual operating expenses and the plant investment of the Atomic Energy Commission; taken from the Semi-Annual Report of the Commission to Congress, January 1957.

A few phases of the atomic-energy effort can definitely be designated as war- or peace-oriented. Thus, the money being spent for research on the methods of detonating bombs to gain high efficiency is certainly dedicated to war, with little conceivable constructive application. At the other extreme, the money used to produce radioisotopes for treatment of cancer represents a beneficial use of atomic energy with no military implications. These two cases are extremely easy to compartmentalize, but they represent only a small part of the $2 billion per year.

An extremely large part of the expenditure, on the other hand, goes to the production of *fissionable materials,* this is, plutonium and uranium-235. These materials are made in large nuclear reactors at the Hanford and Savannah River sites, or the isotope-separation plants in several places throughout the country. When these materials are prepared, however, they are not immediately used but are set aside in storage. And at that stage no one can say whether the fissionable materials are destined for military or for peacetime uses. They can be quickly put into atomic warheads, they can serve as fuel to drive a submarine, they can be used to construct a reactor to produce valuable radioisotopes, or they can be consumed in a large plant, being converted into many thousands of kilowatts of electric power.

Thus who can say what is the intended use of the large amount of money used for production of fissionable materials? Whether these materials are destined for peace or for war depends not on the way in which this year's budget has been written by Congress, but on the way in which political actions are taken this year and in the next decade. The production of these materials is truly a phase of atomic energy applicable to peace *and* war. Any worthwhile plan whose object is to gain the benefits of the atom and avoid its destructiveness must take into account the fact that most of the atomic-energy activity is directed to peace and war at the same time and that strongly controlling one phase of the program will inevitably affect the others. To attempt to halt the progress of science and engineering in a certain sphere of activity by arbitrary means is to do great harm to all science and engineering. A worthwhile plan for control of nuclear energy must provide for the development of all phases in as free a manner as possible. It is a matter of statesmanship to assure that man's life shall be enriched and not destroyed by the developments, rather than to halt a branch of research by edict.

This brief preview of the intimate relation of the good and bad aspects of fission is a mere statement, certainly lacking conviction unless bolstered by the solid facts of nuclear energy. But to attain not only conviction but an understanding of the way in which the basic facts of nature, here of the fissioning and fusing nuclei, can benefit or harm mankind, requires some knowledge of nuclear science. Fortunately, the nuclear science needed is based on a few fundamental properties of matter that require for their understanding only some mental effort, rather than long technical training. It is indeed fortunate that these facts can be grasped by the intelligent layman willing to devote the necessary time. It is only when armed with this understanding that he can make sensible decisions on the disposition, control, and proper emphasis in the development of atomic energy. We turn then to a consideration of the fundamentals of nuclear science, of the facts of fission and fusion, an understanding of which has become one more task of the good citizen of the modern world. And it will be a pleasant task, we hope, for the way in which energy is firmly held by neutrons and protons within the submicroscopic nucleus, yet is released by the violent eruption of fission, is not without interest, wonder, and even beauty.

CHAPTER 2

FUNDAMENTALS OF FISSION AND FUSION

> *Atom-Powered World Absurd, Scientists Told—Lord Rutherford Scoffs at Theory of Harnessing Energy in Laboratories.*
>
> —HEADLINE OF FRONT-PAGE STORY,
> *New York Herald Tribune,*
> SEPTEMBER 12, 1933

All the widespread atomic-energy activities of the present time have their origin in a fundamental phenomenon of nature, the explosive splitting of heavy atoms that is known as *fission.* Since its discovery in 1939, it has been the primary factor in the mushrooming applications of atomic energy to war and to peace. Long before that date, reactions had been known that could liberate energy from deep within the atomic nucleus; in fact, as early as 1914 the conversion of matter itself into energy, in accord with Einstein's equation, had been demonstrated on a small, essentially atom-by-atom, scale. But fission was a completely new, and even an unexpected, process, a much more violent explosion than the previously known nuclear reactions. In addition, it had a peculiar property by which, under proper conditions, the explosion could spread to other nearby atoms, thus propagating itself and releasing macroscopic amounts of energy. Allowed to happen quickly enough, this process would constitute a bomb explosion, in principle of unlimited extent, rather than the release of energy by individual atoms, one at a time, that had been already attained.

The reasons for the tremendous difference in energy released between nuclear burning, which is fission, and the usual chemical burning, say of coal, gasoline, or even TNT, involve the basic structure of matter. Fission and chemical burning differ fundamentally, not merely in magnitude. Just as in order to understand the burning of coal one needs some rudiments of chemical knowledge, so for the understanding of nuclear burning some of the fundamentals of nuclear structure are required. These basic facts of nuclear physics, however, are not of such great subtlety as to require extensive mathematical training for their understanding. In fact, because of their basic nature, these facts have a certain inherent simplicity, which implies that they can be grasped without undue effort. So rather than making bald statements, such as "one pound of uranium can equal *x* tons of coal," let us proceed instead to an examination of a few basic facts of nuclear structure. We then can understand and appreciate, with a little effort, the mechanism of fission and the reason why it can produce energies a million times greater than chemical burning. The sensational statements may of course be true, but, if we understand *why,* they leave the realm of science fiction, and our appreciation is deepened greatly by understanding.

We must examine how neutrons and protons form nuclei, how nuclei and electrons form atoms, how atoms in turn are built into the common materials we know as water, iron, copper, and so on. Knowledge of the way in which these fundamental particles combine together to form ordinary matter will then show how in the reverse process, the destruction of matter itself, such tremendous forces of nature are released.

Atoms and Molecules

When we speak of the manner in which two atoms of hydrogen combine with one of oxygen to form water, or of the combining of coal (which is carbon) with oxygen to form carbon dioxide, in the process known as combustion, we are speaking not as nuclear physicists but as chemists. We are speaking of *chemical reactions,* of the way in which the simplest ordinary forms of matter, or *elements,* combine to form more complicated substances, known as *compounds,* which can in turn be split into their elements. Such reactions as the formation of water and carbon dioxide from their elements are particularly simple chemical reactions, familiar to chemists for generations. They involve relatively slight modifications of the structure of matter compared with the profound changes now known in nuclear physics.

For a half-century or so, the basic facts of the atomic structure of matter have been well established. We know with certainty that all materials are made of *atoms,* even though these particles are far too small to be seen individually by the most powerful microscope. A particular substance that is composed of one kind of atom only is known as an *element.* Thus the gas oxygen, which comprises 20 percent of ordinary air, contains oxygen atoms only and is thus an element; so are hydrogen, carbon, copper, zinc, tin, each consisting of one specific type of atom alone. When the atomic age opened, 92 such elements were known to man. It had required the patient effort of chemists for many generations to isolate and systematize these 92 elements, ranging from hydrogen, containing the lighest and simplest atom, to uranium, with the heaviest. Through the help of atomic energy man has now succeeded in synthesizing several new and heavier elements to be added to the list. The most recent of these are einsteinium, fermium, and mendelevium, named after three giants of modern science, Einstein, a German, Fermi, an Italian, and Mendeleev, a Russian.

An atom of any element is the smallest unit of that material whose existence is possible. If we divide some oxygen gas, for instance, into portions of smaller and smaller size, the gas remains oxygen until we reach the ultimate limit of one particle, or one atom of oxygen. Further division would change the basic characteristics of the atom; it would no longer be oxygen. In other words, we then would have split the atom of oxygen, a change of profoundly different nature from the mere separation of oxygen atoms from each other—a change furthermore requiring tremendously more energy, as we shall learn.

When atoms are combined in chemical reactions, as, for example, when an atom of oxygen combines with two atoms of hydrogen to form water, the atoms themselves are practically unchanged. If we could look with some sort of super microscope at a *molecule* of water —the word molecule being the name applied to the combination of unlike atoms that forms the smallest unit of the chemical *com-*

pound—we would recognize the atoms of hydrogen and oxygen for just what they are, atoms still retaining their individuality. They are held together as a stable, relatively inert molecule of water by the electrical attractions of their outermost regions only, the central parts of each atom being completely unaffected by the other atoms. The correct use of these terms that we are learning so fast—atom, molecule, element, and compound—may perhaps be aided by Fig. 2, which illustrates the various relations among them. The precise manner in which various atoms are held together in molecules is an extremely complex matter, which forms the basis of the entire science of chemistry, but which is not of direct interest to us.

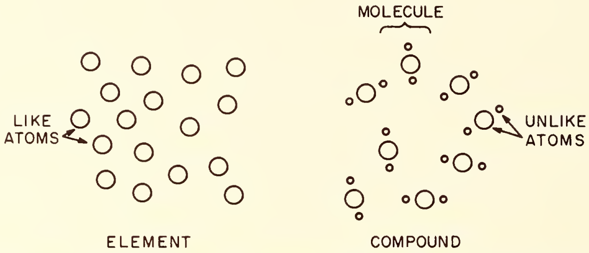


Fig. 2. The smallest part into which an element may be divided is an atom, whereas for a compound the smallest part is a molecule, which in turn is composed of several kinds of atoms.

Our primary concern here is rather to make clear that it is only the outer layer of the atom that is involved in chemical combinations or changes, that is, only those peripheral *electrons* loosely attached to the remainder of the structure of the atom. Electrons are the smallest possible units of electricity, being negatively charged and of extremely light weight. Moving through wires, they constitute electric currents, or hitting the screen of a television tube, they produce the visible image. Relatively minor changes in the spatial arrangement of the electrons at the surface of the atom account for the way in which atoms combine to form molecules. Consideration of these changes explains why a particular number of one type of atom combines with the others in a molecule, for example, and the ease with which they come together or can be pulled apart. Those electronic changes *are* chemistry and they are manifested by the millions of compounds that can be built up from the basic 92 elements that exist in nature.

The Internal Structure of the Atom

The behavior of atoms in chemical changes was well understood in a practical way even at a time when essentially nothing was known about the internal structure of atoms. Little needed to be known about this structure, for it did not change during chemical processes, which involve only a few electrons on the atom's surface. At the present time, however, we not only know much more about this internal structure but know how to change the structure itself. The methods necessary for changing the interior of the atom require vastly more energy than those used for producing chemical reactions, a reflection of the fact that the forces holding the individual atom together as a unit are much greater than those exhibited in its combination with other atoms.

When the principles of chemical reactions were empirically understood, and nuclear physics was nonexistent, atoms were visualized as hard, structureless spheres, except for the surface charges, which accounted for chemical effects. In 1911, however, the British physicist Rutherford showed that essentially all the weight of an atom is concentrated in a tiny central speck of dense matter, most of the volume of the atom being occupied by rapidly moving, lightweight electrons. All these electrons are identical, the ultimate particles of electricity that we have already discussed. Nevertheless it is only the few outermost electrons that, in circulating around the central mass, interact with electrons of other atoms and thus cause the formation of molecules.

The structure of a typical molecule is illustrated in Fig. 3, which is a diagram of a molecule of water, consisting of two atoms of hydrogen and one of oxygen, or H_2O, as we would express it in chemical notation. The oxygen atom possesses eight electrons and the hydrogen atoms one each; the resulting combination is particularly stable. The stability arises because the electrons tend to form "shells" around the nucleus, containing two electrons in the first shell, eight in the next, then eighteen, and so on. When the combination of several atoms results in a filled shell, as the shell of eight for oxygen in Fig. 3, the resulting molecule, in this case water, is very stable.

It is the massive central speck of matter—the *nucleus*—that is the source of atomic energy. In addition to containing most of the weight of the atom, the nucleus is positively charged electrically with an amount of charge just sufficient to equal the negative charge of the circulating electrons. Because of this balance of charge, the atom as a whole is electrically neutral, which is a necessary state of affairs, for otherwise the electrical repulsion between atoms would cause all matter to fly apart. The nucleus is completely unchanged in even the most violent chemical reactions. When, however, by means we shall soon consider, the nucleus is changed, forces are involved that are enormously greater than those produced by the electrons responsible for chemical changes. It is unfortunate that the term "atomic" energy has become so firmly connected with the energy resulting from the powerful nuclear forces, for it is actually "nuclear energy." To change the name of the "Atomic Energy Commission" to the "Nuclear Energy Commission" is a bit too much to expect, perhaps, so that we must interpret the phrase "atomic energy" to mean "energy from the nucleus of the atom."

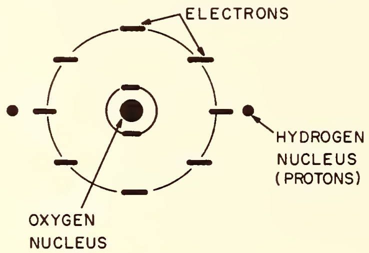


Fig. 3. The structure of nuclei and electrons in a molecule of water, H_2O. The stability of H_2O results because shells containing two, then eight, electrons around nuclei are particularly stable and the combination of two hydrogen atoms with one oxygen atom produces these configurations of electrons.

The Nucleus

These simple facts about the atomic nucleus were known for many years before it was discovered just what the constituents of the nucleus itself were. The nucleus of the lighest atom, that is, *hydrogen,* seemed to be of a particularly simple nature and was called the *proton.* As the hydrogen atom contains only one circulating electron, the proton necessarily has a charge equal to that of the electron but of the opposite, or positive, sign. It is much heavier than the electron, however, having a weight about 1800 times that of the electron. Nuclei of all other atoms are heavier than that of hydrogen and have larger positive electric charge to balance the greater number of surrounding electrons, which is eight, for example, in oxygen (Fig. 3). It was clear, however, that the nuclei other than that of hydrogen contained some other particles in addition to protons, for their weight was much greater than one would expect from protons alone. Thus the ninety-second atom in order of weight, namely *uranium,* has an electric charge on its nucleus 92 times as great as the proton but a weight over 200 times that of the proton.

In 1932 a new fundamental particle was discovered that was immediately of great value in explaining the structure of the nucleus. This new particle, the *neutron,* had a weight almost exactly that of the proton but carried no electric charge at all. It was almost immediately obvious that this must be the additional type of particle that is present in nuclei, enabling them to have high mass but without exceptionally high electric charge. Thus a particular type of uranium, which has a weight 235 times that of the proton and a charge 92 times that of the proton, can easily be explained by assuming that it contains 143 neutrons within its nucleus.

Thus we see that it is relatively simple to account for the weight and the electric charge of an atom. The weight of an atom, on the scale adopted by the chemists, technically the *atomic weight,* is given simply by the number of neutrons plus the number of protons it contains, the electron's weight being negligible. The atomic weight of ordinary hydrogen is thus 1, of beryllium it is 9 (4 protons plus 5 neutrons), and of oxygen it is 16 (8 protons plus 8 neutrons), as indicated in Fig. 4. The electric charge on the nucleus, however, is given by the number of protons alone. The number of electrons surrounding a nucleus must be equal to the number of protons because matter itself in its undisturbed state is electrically neutral. The behavior of the atom in chemical reactions is determined almost entirely by the number of electrons it contains, as illustrated in Fig. 3 for the formation of a molecule of water. As a result of the close connection between electron structure and *atomic,* as contrasted to *nuclear,* interactions, the best way to classify different atoms or elements is by the number of electrons, which is the same as the number of protons. This number is called simply the *atomic number* and is 1 for hydrogen, 4 for beryllium, 8 for oxygen, 92 for uranium, 94 for plutonium, and so on, up to the highest atomic number thus far obtained, which is that for mendelevium, namely, 101.

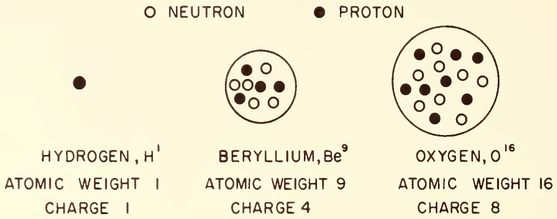


Fig. 4. The manner in which the nuclei of several elements are made up of neutrons and protons.

Isotopes

We meet one slight additional complication when we speak of the weights of various atoms. It is possible for individual atoms of a single element to have different numbers of neutrons in their nuclei. However, because the chemical properties of atoms are determined by the number of electrons, as we have just seen, these atoms of different weight, but of the same atomic number, will behave alike in all ordinary chemical manifestations. Thus it is easy for us to see that hydrogen, which usually has one proton alone in its nucleus, can also exist with a nucleus containing one proton plus one neutron. This second kind of hydrogen, heavier than normal hydrogen, will act essentially the same as hydrogen does, say in combining with oxygen to form water. Introducing the technical name for this situation should not complicate its essential simplicity, so we should here speak of *isotopes,* that is, atoms of a particular element that differ in weight but not in charge. Thus, reverting to the technical terminology, we say that heavy hydrogen, also called *deuterium,* is an isotope of hydrogen that has an atomic weight of 2. There is also a third isotope of hydrogen, containing two neutrons and one proton, and this type is called *tritium,* an important constituent of the H-bomb.

Perhaps one might wonder why we bother to emphasize isotopes when the different isotopes of a particular element behave so nearly the same in all ordinary interactions. Heavy hydrogen, if combined with oxygen, for example, forms heavy water, which is almost completely indistinguishable from ordinary light water. It would perhaps be a bit expensive as a drink but otherwise would not differ from ordinary water in the slightest degree practically. However, it is of the most fundamental importance to understand isotopes when we come to discuss the principles of nuclear energy. The reason is that, when we consider the profound effects resulting from the change of one atom into another that results from a *nuclear* change, the exact constitution of the nucleus involved is of tremendous importance. In other words, even though heavy water and ordinary "light" water act practically the same in most processes, they are vastly different when it comes to a matter of nuclear changes. The atomic similarity, but nuclear difference, of the structure of heavy and light water is shown graphically in Fig. 5. As another example, we shall soon learn that two isotopes of the uranium atom, one containing 235 nuclear particles and the other containing 238, differ profoundly in nuclear behavior. The former of these can be used for the atomic bomb, or for the controlled nuclear chain reaction, but the latter simply does not exhibit the basic phenomena necessary for the chain reaction.

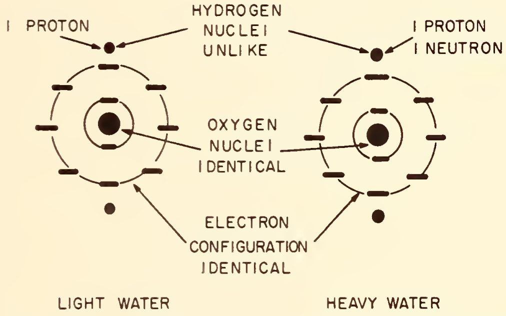


Fig. 5. The structure of light and heavy water; the atomic structure (that is, the electron configuration) is identical for both molecules but the nuclei of the hydrogen atoms are different.

Because of the importance of the difference between isotopes it will be very convenient for us to learn the simple terminology used to designate isotopes in nuclear studies. Thus we write H^1, H^2, and H^3 for the three isotopes of hydrogen, whose nuclei, containing zero, one, and two neutrons, are called the proton, deuteron, and triton, respectively. Also C^{12}, by far the most abundant type of carbon, contains 6 protons and 6 neutrons, whereas C^{13} and C^{14} contain one and two extra neutrons. (The latter is the isotope that is so useful in fixing the age of ancient materials in the range of thousands of years.) We also write U^{235} and U^{238} for the best-known uranium isotopes, and Pu^{239} for the man-made plutonium isotope, so important to atomic energy. Sometimes we add a subscript, as ${}_6C^{12}$, ${}_{92}U^{235}$ or ${}_{94}Pu^{239}$, to remind ourselves of the number of protons or positive charges on these nuclei, although the subscript is redundant because the fact that a particular atom *is* carbon or uranium or plutonium, as shown by the symbol C, U, or Pu, implies that it is the 6th or the 92nd or the 94th element.

Stability of the Nucleus

Several interesting facts soon emerge when we examine the 101 known elements, each of which has a number of isotopes—running to more than twenty in the case of tin, for instance. In a particular isotope the number of neutrons relative to the number of protons may be unusually large or small. In this case the nucleus is *unstable* and tends to return to a more normal neutron-proton relation by emitting energy in some form. This emission of energy from unstable nuclei is of tremendous practical importance, and even danger, in the atomic-energy industry.

The lightest nuclei are most stable if the numbers of neutrons and protons are approximately equal, but the heaviest nuclei have a larger number of neutrons than protons. This fact is not difficult to state in words, but for a scientist it can be shown much more accurately by means of a graphical presentation. We include a graph (Fig. 6) primarily to indicate how the facts of nature can be shown in this way, but for those who prefer to be less technical the words will do: elements of low atomic weight tend to have equal numbers of neutrons and protons in their nuclei but for increasing atomic weights a growing excess of neutrons occurs.

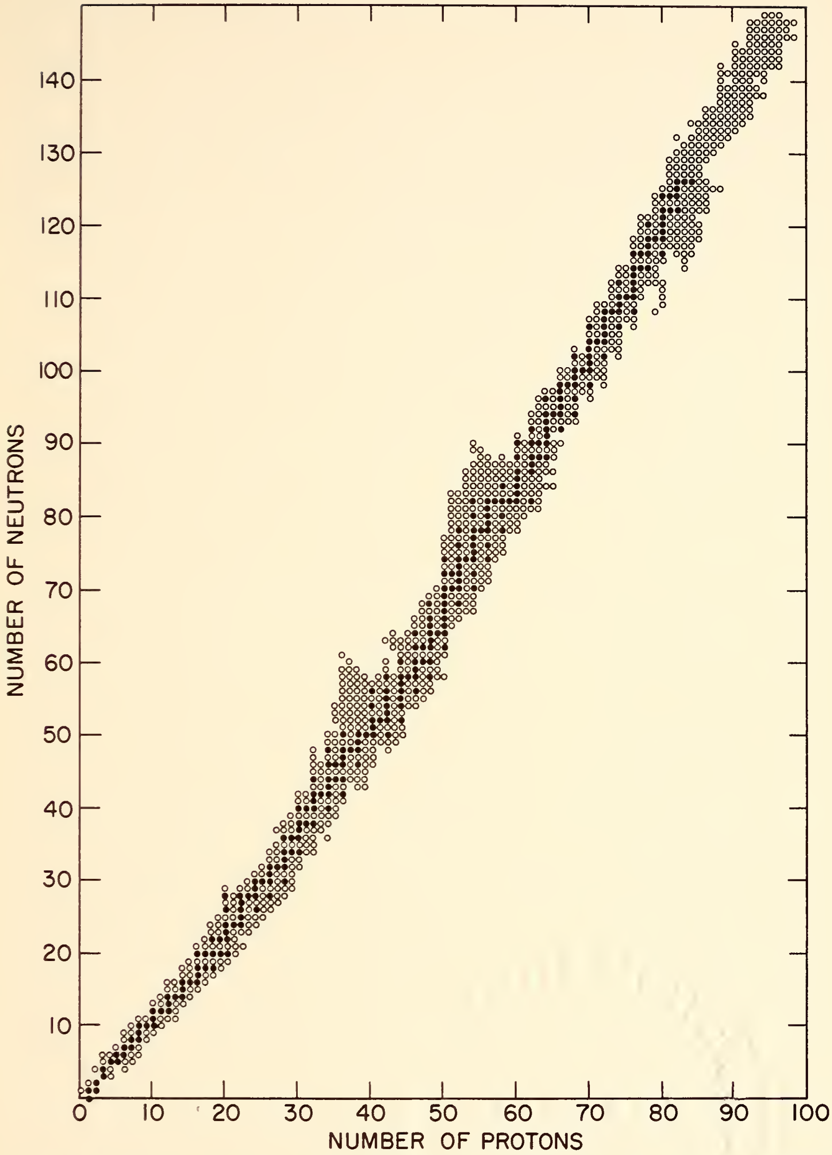


Fig. 6. In this graph the number of neutrons and protons is shown for the stable and unstable nuclei. The unstable nuclei, shown as open circles, emit radiation and transform into stable nuclei, shown by solid circles. For example the three points in a vertical line for one proton are H^1, H^2, and H^3, the last being unstable. For light nuclei the number of neutrons is about equal to the number of protons but for heavier nuclei the number of neutrons is larger.

In the figure the numbers of neutrons and of protons are plotted for very many nuclei, the solid dots corresponding to the stable isotopes. The center of the region of the solid dots thus gives the average configuration of these stable isotopes, that is, the average number of neutrons for any atomic number (number of protons). The position of this curve shows that the average neutron number is 70 for atomic number 50, and 120 for atomic number 80. The open circles denote isotopes that exist but are unstable. These unstable isotopes give out their energy by radiation and thus transform into stable nuclei, that is, those shown by solid dots, and in this way "move" toward the position of stability. We thus have the reasoning behind another technical term for these unstable isotopes that emit radiation in changing to stable forms. They are called *radioisotopes* because they are "radiation-emitting isotopes."

There is a tremendous range in the lack of stability of radioisotopes. Some of them can exist for only a few millionths of a second before they change to stable forms, by the process known as *radioactive decay,* whereas others are almost stable and may exist for thousands, millions, or even billions of years before transforming. The unstable isotopes that are almost stable have been found to occur naturally and these were known as early as the turn of the century. The most famous of these almost stable atoms is radium, which was successfully isolated by the Curies in France and since then has been widely used for medical treatment.

The great magnitude of the forces holding the neutrons and protons together in the nucleus is revealed when one of the unstable isotopes disintegrates. The energy given off at the disintegration is approximately one million times the energy represented by a chemical change, which involves only the outermost electrons of the atoms concerned. In atomic and nuclear processes energies are usually expressed in terms of *electron volts,* 1 electron volt being the energy gained by one electron being acted on by a voltage of 1 volt. Thus the energy that appears in a chemical change, such as the uniting of a carbon atom with two oxygen atoms, is of the order of a few electron volts. On the other hand, the energy released when an unstable nucleus is transformed to a stable one is approximately 1 million electron volts. This tremendous difference in magnitude is a direct reflection of the extremely strong forces that hold the neutrons and protons together, as compared to the electrical forces that hold the electrons in the outermost region of the atoms.

The precise nature of the tremendous forces inside the nucleus is not known, but almost certainly it involves the newly discovered particles called *mesons,* of mass heavier than electrons but lighter than neutrons and protons. These mesons fly rapidly back and forth between the neutrons and protons in the nucleus and by this interaction hold them firmly together. Incidentally, it is to learn about the mesons and the forces that they create in the nucleus that large machines such as cyclotrons, cosmotrons, and bevatrons are built. For in these large machines protons and neutrons are given energies of many million electron volts and then hurled at each other. The collisions occur with such violence that the mesons are pulled away from the neutrons and protons and brought out in the open, so to speak, where they can be studied.

The Einstein Mass-Energy Equation

Even though the nature of the binding between nuclear particles is still only dimly understood, it is fortunately possible to predict with great accuracy just how much energy is evolved when the unstable nuclei are transformed. The strong binding is the reason for the large amounts of energy involved but knowledge of the complicated mesonic interaction is completely unnecessary in calculating energy changes. The accuracy of prediction is possible because of Einstein's famous *mass-energy equation,* which predicts that matter itself can be transformed into energy, and, furthermore, tells us exactly how much energy will appear in such a transformation. When an unstable nucleus emits radiation the stable nucleus that remains after the radiation weighs slightly less, or, in other words, has less *mass,* than the original nucleus. *The small amount of mass that has disappeared is transformed into the tremendous amount of energy represented by the radiation.* Here we have a simple illustration of Einstein's principle—the conversion of mass itself into energy—which is the fundamental fact behind the entire atomic-energy field.

Einstein's equation is so basic to the field of atomic energy that we should master its principles, even though it will lead us to a few more technical terms and a bit of mathematics. The equation itself looks very simple,

$$E = mc^2,$$

which is fortunate for purposes of our explanation, although in actuality it is the result of most profound considerations involving relativity and time as a fourth dimension. We may omit these considerations with no loss in accuracy, however, and examine the equation in its simple but elegant form. Translated into words, this equation says that energy E is equal to mass, denoted by m in the equation, multiplied by the velocity of light c, not once but twice, in other words, c "squared." It is this simple arithmetic process that tells exactly how much energy will appear when an amount of mass m disappears, as in the case of an unstable nucleus emitting radiation.

If one uses the actual numbers that go with this equation the tremendous magnitude of nuclear power becomes obvious. The magnitude is so great simply because the velocity of light, c, is so high—186,000 miles per second. In nuclear physics we use the *metric system,* in which c is 3×10^{10} centimeters per second, that is, 3 followed by ten zeros—30,000,000,000. This number multiplied by itself, that is, squared, becomes 9×10^{20} or 9 followed by twenty zeros, a truly imposing number, which we shall not write at length, the shorthand 9×10^{20} being far more convenient.

It is not worth our while to follow through the detailed arithmetic necessary to convert these large numbers into more familiar terms in order to grasp the significance of $E = mc^2$. It is simply that even a small amount of matter that disappears is manifested by the appearance of an amount of energy so large that it is difficult even to comprehend. The arithmetic that we have outlined shows, for example, that if m is taken to be 1 pound—incidentally, it makes no difference what material is considered—then the energy resulting from its conversion would be 11 billion kilowatt hours. It is hard to visualize this amount of energy, but as an aid it is roughly the amount of electrical energy used by a city of 10,000 inhabitants in one complete year. The comprehension of the energy resulting from 1 pound of matter is helped if we convert to other units. Thus, this

1 pound of material on disappearance would give the same amount of energy that is obtained from the burning of 200 million gallons of gasoline or 1,500,000 tons of coal. Of course, $E = mc^2$ does not tell us *how* we can convert, say, 1 pound of water into energy. It is rather a principle of universal applicability that deals with the balance between mass and energy, rather than the detailed mechanism of their conversion. Actually, the Einstein theory was developed about a half-century ago and, while its general validity was recognized, the practical production of energy on a large scale was not visualized at that time simply because no mechanism was thought to be feasible.

It is Einstein's equation used in the manner we have just described, but applied to individual atoms, that tells us exactly how much energy will appear when one atom is transformed into another. If this transformation is spontaneous, as it is for, say, radium, the transformation must of course be from a heavier to a lighter atom, otherwise there would be no available mass for conversion into energy. The weights of all atoms have been measured with extreme accuracy and is only necessary to compare the weight of one atom with that of another to see what energy will be evolved if the first atom should transform into the second. Incidentally, the points on Fig. 6 representing unstable nuclei are related to the others in that they are heavier and transformations on the diagram from open to solid points, toward greater stability, represent decrease in mass.

The natural transformations such as the disintegration of radium represent only those cases in which an atom transforms into another atom of almost the same size. In other words, using the terms we have already defined, the natural transformations are those in which the atomic weight and atomic number change by only small amounts, say one or two units. The radiation that is emitted during the transformation consists only of a few well-known types. These radiations are called alpha, beta, and gamma rays and were known as long ago as 1900, when many of their properties were studied by the Curies. The *alpha rays* are identical with the nuclei of helium atoms, He^4, and can easily be described, using what we now know of nuclear structure, simply by saying that they each contain two neutrons and two protons. The *beta rays* are high-speed electrons;

hence, as we know, they have very low mass and have negative electric charge. The *gamma rays* have no mass or charge and are the same as x-rays, but have shorter wavelength and hence higher energy. Some of the simple properties of the three types of radiation are shown in Fig. 7.

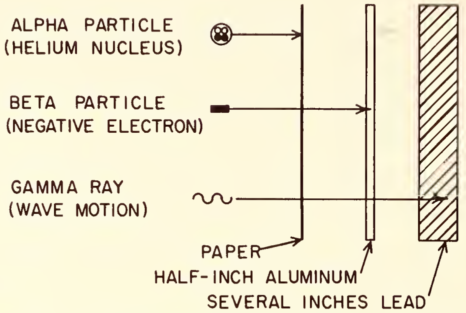


Fig. 7. The penetrating power of alpha, beta, and gamma rays, shown by the amounts of material necessary to stop them.

We shall later be concerned with the detailed properties of these radiations, for they determine the manifold uses of the radioisotopes obtainable in large quantities from nuclear reactors. In the present connection, however, it is sufficient for us merely to realize that these radiations carry off the energy predicted by Einstein's equation when an unstable nucleus transforms into a lighter, more stable form.

Man-Made Nuclear Transformations

The changes of nuclei from one form to another that we have just discussed are spontaneous transformations of unstable nuclei, always involving a decrease in mass and emission of radiation. One cannot control these disintegrations, for their rate is inherent in the structure of the nuclei involved, being largely controlled by the amount of available energy; in general, the larger the amount of energy emitted, the more rapid the occurrence of the transformation. Of the elements found in nature, only the heaviest, with a few minor exceptions, exhibit instability and spontaneous transformations.

However, the British physicist Rutherford showed that it was possible to transform atoms from one form to another by artificial means, and thereby, with this so-called *artificial transmutation,* the possibilities of nuclear changes increased tremendously. It became possible to change one element to another throughout the entire range of elements from hydrogen to uranium, and even to make new unstable isotopes, which had not been found to occur in nature previously. Radioisotopes could thus be made of any desired elements, for example, carbon, iron, or lead, which until then had been considered completely stable.

Rutherford showed that the transformation of one nucleus to another could be induced if the nucleus could be hit by a high-speed particle. Of course this bombarding particle must have great energy because it necessarily must change the nuclear structure, that is, add or remove protons or neutrons, which are held together with nuclear forces of great strength. Rutherford actually used alpha particles in his pioneering experiments for bombarding nuclei.

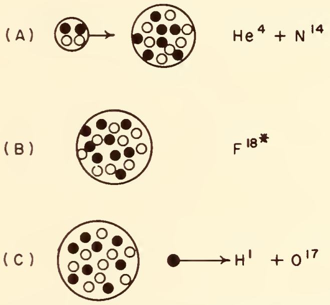


Fig. 8. The first artificial transmutation of nuclei, found by Rutherford, in which nitrogen was changed to oxygen by bombardment with alpha particles. In (*A*) the alpha particle impinges on the nitrogen nucleus, in (*B*) the resulting short-lived fluorine nucleus is shown, and in (C) are the final products, an energetic proton and an oxygen nucleus.

The alpha particles were obtained from the disintegration of heavy elements such as radium, which emit alpha particles with energies of several million electron volts. The historic nuclear transformation first produced by Rutherford, in which nitrogen was changed to oxygen, is shown in Fig. 8. The discovery was made by observing the energetic protons produced in the transformation by allowing them to hit a fluorescent screen where they gave rise to tiny flashes of light.

At the present time, however, much more potent sources of bombarding particles are available, such as cyclotrons or the beams of neutrons that emerge from nuclear reactors. Even before nuclear reactors had been built, the use of bombarding particles from cyclotrons had made possible, in the thirties, the production of radioisotopes of many elements on a much greater scale than was possible with natural alpha-particle sources. The neutron intensities now available in nuclear reactors are so great that almost all of the large number and quantity of radioisotopes so widely used are easily produced.

In the case of artificial nuclear transformations, such as those used in the production of radioisotopes, Einstein's equation still applies. In general, however, in the making of radioisotopes, the equation applies in a reverse sense to that we have already considered. The unstable isotopes are heavier than the stable isotopes to which they decay. Thus to make the former from the latter requires the transformation of energy into matter in order to increase the mass by the required amount. This energy is contributed by the energy of motion of the bombarding particle; Einstein's equation together with a knowledge of the weights of the atoms concerned tells us exactly how much bombarding energy is needed. As we would anticipate from our previous discussion, the energies involved are of the order of millions of electron volts because we are changing the nuclear configurations.

A point of great practical importance applies to these nuclear transformations, whether produced by bombardment in cyclotrons or with the particles resulting from natural disintegration, as of uranium. It is simply that the *total* amount of energy involved in producing a nuclear transformation is very small even though the energy change relative to a single nucleus is usually large. The reason is that, even though millions of atoms may be disintegrating every second in a piece of a radioactive substance, the total number of atoms present is so much greater that the number disintegrating is only a tiny fraction of the whole. Likewise, if bombarding particles from a cyclotron are sent into a block of material, the number of atoms hit and transformed by the bombarding particles is always an extremely tiny fraction of the total number present.

These facts follow from the large numbers of atoms present in matter and the extremely small size of their nuclei, which must be hit by the bombarding particles to produce a transformation. One gram of radium for example, which is about one-thirtieth of an ounce or a piece about the size of a pea, contains 3×10^{21} atoms. Even though 40 billion (4×10^{10}) radium nuclei disintegrate spontaneously every second, 1600 years must elapse before half the piece has been transformed! The rate of energy evolution from the gram of radium is thus extremely small, actually only one hundredth of a watt or one thousandth the energy consumption of a small, 10-watt, lamp.

Atoms themselves are very small, as follows from the large numbers contained in matter, and their nuclei are much smaller. A typical atom is 10^{-8} (or one hundredth of a millionth) inch in diameter, but its nucleus about ten thousand times smaller, or 10^{-12} (a millionth of a millionth) inch. Although it is impossible to visualize these exceedingly small dimensions, they do convince us why a beam of millions of bombarding particles per second will transform only a small part of a bombarded material.

Thus, primarily because of the large numbers of atoms involved, it is extremely difficult to produce *gross* effects, that is, to transform a large fraction of a piece of material by artificial transmutations, or to have sizable amounts of energy result from spontaneous disintegration. During the thirties, transformations produced by cyclotron bombardment were very important in giving information about the structure of matter, but they were completely insignificant relative to the numbers needed to obtain useful gross effects.

At this period, some scientists speculated about the great amount of energy that could be evolved if sizable numbers of atoms could ever be caused to transform. However, no methods were known by which the tremendous numbers of transmuted nuclei could be attained. The speculations were considered as scientific daydreams and were deprecated by many authorities, including Rutherford himself, as shown by the quotation heading this chapter. Nobody suspected that a process was to be found that would change the picture completely and make it possible to transform not only pounds, but even tons, of material and to produce almost unlimited amounts of energy. This discovery, of course, is the process of fission, which seems so straightforward and obvious to us now but whose existence was not even hinted during the twenties and the thirties, when nuclear transformations of only small numbers of atoms could be carried on and even that necessitated laborious bombardment.

Fission

During the period 1925–1935 many nuclear transformations were produced using as bombarding particles protons, alpha particles, or gamma rays, these usually being obtained from the particle-accelerating machines, primarily the cyclotron, that had recently been developed. After its discovery in 1932, the neutron became a bombarding projectile of extreme importance. The reason for the great efficacy of the neutron is that it has a relatively large mass, hence a large amount of energy, but carries no electric charge and as a result can penetrate through the electric field surrounding the nuclei of atoms. Thus even very slowly moving neutrons can reach the nuclei of atoms and add sufficient energy to cause a transformation. Neutrons were found to be particularly effective in making radioisotopes and were so used for almost every element.

When uranium, the heaviest known element, was bombarded with slow neutrons it was first thought that new elements heavier than uranium had been created. However, the complexity of the chemical behavior of the resulting products led two German scientists, Hahn and Strassman, to the correct explanation in December 1938. By chemical behavior of the products resulting from the interaction, they identified the radioisotopes produced, not as new elements heavier than uranium, but as isotopes of well-known elements about half as heavy as uranium. They thus had shown that uranium, after absorption of a slow neutron, can split approximately into halves—a process that soon became known as *fission.*

Up until the time of the discovery of Hahn and Strassman, all nuclear transformations, as we have seen, were relatively minor in nature, involving changes in atomic weight or atomic number by only one or two units. Here was a vastly different type of transformation, however, one in which the atomic weight and number were changed profoundly, being divided by two, approximately. As the weights of all atoms were known reasonably well, it was immediately obvious from a comparison of the weight of the uranium nucleus with the weights of the two nuclei formed after fission that a large amount of matter must disappear in the process. The change in weight was approximately one hundred times that for the usual nuclear reactions. Thus inevitably, in accordance with Einstein's equation, one hundred times as much energy as usual must be produced, actually about 200 million electron volts.

As soon as the revolutionary discovery of Hahn and Strassman was made known to the scientific world, experiments were quickly made that verified the predicted large release of energy. The energy appeared as energy of motion, that is, the two halves into which the uranium nucleus split moved apart with tremendous speed. Within a few months after the discovery most of the fundamental properties of fission were known, and, incidentally, freely published, for there was no secrecy in nuclear physics in 1939.

Let us now look a little more closely at this explosive phenomenon of fission, induced by the absorption of a slow neutron, that was to bring to a level of possibility the practical conversion of mass into energy. When any nucleus absorbs a neutron, it acquires some energy, which can be considered as heat energy, just as a block of wood would be heated slightly if a bullet, fired into it, is stopped in the block. The behavior of the nucleus after it has acquired some energy, however, is more nearly like the behavior of a drop of liquid than a block of wood. In fact, many of the properties of nuclei are computed from the well-known properties of liquids; thus we talk about the *liquid-drop model* of the nucleus.

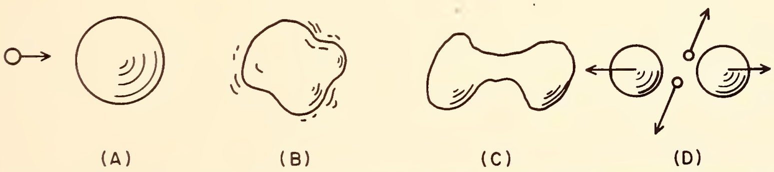


Fig. 9. The liquid-drop model of the uranium nucleus in fission. (*A*) A neutron approaches the nucleus; (*B*) the resulting nucleus begins to vibrate; (*C*) the nucleus begins to split; (*D*) fission fragments and neutrons fly away from the disrupted nucleus.

If a drop of liquid is heated it begins to oscillate violently, waves move around in the surface boundary, and parts of it may evaporate or boil off. In just the same way the absorbed energy of a nucleus causes oscillations of the nuclear matter similar to those of the liquid drop. For a heavy nucleus, such as uranium, the oscillations may become so violent and the configuration so unstable that there is a high probability, as shown in Fig. 9, for disruption into two approximately equal droplets. This picture, or analogy, crude as it may seem, gives a surprisingly accurate description of the process of nuclear fission. It even predicts, for instance, that, as the two parts of the uranium nucleus move away from each other, their oscillations are so violent that bits of the nuclear matter may fly off. These small bits are usually neutrons, and, as we shall see later, are of tremendous importance in producing the chain reaction.

Roles of U^{235} *and* U^{238} *in Fission*

The discovery of fission and the early experiments with it were made using the ordinary element uranium as it occurs naturally, consisting almost completely of U^{238} with slightly less than 1 percent of U^{235}. The basic mechanism of fission that we have been considering will enable us to understand how it is that only the U^{235} undergoes fission readily. In order to make the fission process take place it is obviously necessary to add sufficient energy that the oscillations become violent enough to cause the marked distortion that leads to disruption. A simple consideration of nuclear structure shows why it is U^{235} and not U^{238} that is much more likely to have sufficiently energetic oscillations, after absorption of a neutron, to undergo fission.

It is a well-established property of nuclei that the individual particles have a strong tendency to exist in pairs, two neutrons binding strongly together, as do two protons. Thus helium, containing a pair of neutrons and a pair of protons, is the most stable of all nuclei, being the only one that will not absorb another neutron. Likewise oxygen, ${}_{8}O^{16}$, with four pairs of protons and four pairs of neutrons, is extremely stable; on the other hand, ${}_{7}N^{17}$, which can be made artificially, is highly unstable and transforms spontaneously into ${}_{8}O^{16}$. The transformation occurs rapidly, as is characteristic for a radioactive decay with a large energy release. The isotope ${}_{92}U^{238}$ consists only of pairs of protons and neutrons, 46 of the former and 73 of the latter. The ${}_{92}U^{235}$ isotope on the other hand, although of the same atomic number (hence number of protons) has an odd number of neutrons, 143 (71 pairs plus 1), and hence is less stable. These are all illustrations of the fundamental nuclear property that unpaired particles correspond to heavier mass and to instability.

We can now carry the analysis of *fission energetics* one step further, although the considerations therefore become somewhat more subtle. *After* U^{235} has absorbed a neutron but *before* it has split, it is U^{236}, containing only pairs (46 pairs of protons and 72 of neutrons), which in its *normal* state would be extremely stable. However, since we have formed the U^{236} by adding energy to an already unstable, hence energetic, nucleus, a large amount of energy would have to be emitted by the U^{236} nucleus to reach its normal state, containing no excess energy. Sometimes the nucleus does emit its energy as gamma radiation, resulting in an atom of U^{236} with no excess energy, which lasts for millions of years in a stable condition. However, the most likely happening is that this extra energy, represented by the violent oscillations of the U^{236} nucleus, will cause fission to take place before the nucleus can lose its energy by some other process.

The situation is just the reverse for U^{238}, however, for we add a neutron to a nucleus already stable and form U^{239}, which in its normal state is not stable. Because the nucleus we form would not have to release much energy to become normal U^{239}, it therefore does not have much energy available for the violent oscillations that could lead to fission. Normal U^{239} does exist, but lasts only a matter of a few minutes before disintegrating, because of its unstable nature.

This predicted greater fissionability of U^{235} relative to U^{238} was soon verified by experiments and, as we shall see later, led to the realization that separation of these isotopes is necessary to produce a uranium atomic bomb. This gigantic industrial task is a primary reason why $2 billion were expended on the atomic project during the war.

Products of Fission—Energy, Fragments, and Neutrons

The process of fission, the basic mechanism of which we have been considering, has three principal products, all of great practical importance. They are (1) energy, (2) fission fragments, and (3) neutrons. The amount of energy released in fission is calculated directly from the difference in weight between a uranium atom plus a neutron and the fragments into which the uranium atom splits. The fragments vary somewhat in character, for the splitting is never exactly into equal halves and several dozen different elements are represented by the fragments. The energy released, however, is always about 200 million electron volts, much larger than the energy released in the usual nuclear transformations, which as we have seen is about 1 million electron volts, and enormous compared to the energy release of a chemical reaction, which is of the order of a few electron volts.

In spite of the extremely high release of energy in fission, actually only a small fraction of the weight of the uranium nucleus disappears. The fractional decrease in weight of the uranium nucleus as it splits into fragments is only about one part in one thousand, that is, 0.1 percent. By comparison with the figures we have already given for the complete conversion of matter into energy we can easily obtain the energy release for fission simply by dividing by one thousand. It follows that 1 pound of uranium, if all its atoms were split by fission, would in the process produce 11 million kilowatt hours of energy, equivalent to the burning of 200,000 gallons of gasoline or 1,500 tons of coal. This energy appears first as energy of motion, or *kinetic energy* of the separating fragments. As the rapidly moving fragments collide with uranium atoms, however, they quickly slow down and the kinetic energy is thereby converted into heat, the temperature of the uranium rising accordingly. One of the major practical problems of the atomic-energy industry is the effective use of this heat energy to produce electrical or motive power. This matter we defer to later chapters, however.

The *fission fragments* are usually very unstable because they contain a higher fraction of neutrons than typical stable elements of their weight. This result can easily be predicted from Fig. 6. A symmetrical split of U^{236} would give two atoms of atomic number 46 (palladium) and weight 118, thus containing 72 neutrons each, many more than the 57 neutrons shown by the solid dots of Fig. 6. The fission-fragment atoms therefore are highly radioactive, that is, they are *radioisotopes,* and they return to stable forms usually by emitting several energetic beta particles in succession.

The intense radiations from the fission fragments always accompany the nuclear chain reaction and make it necessary to build large *radiation shields* around nuclear reactors. The radioactive fragments create the danger from *fallout* after atomic-bomb explosions as well but, on the other hand, they are extremely useful in countless fields of research.

The third important result of fission is the production of neutrons. As the fission fragments move apart carrying the large amounts of energy, they are highly unstable because of their large excess of neutrons. Actually, even before they stop moving and long before emission of beta particles commences, several of the excess neutrons are "chipped off" the fragments. The emission is so rapid that it is practically part of fission itself, a mark of the violence of the oscillations leading to fission. Thus, on the average, 2.5 neutrons are emitted during the fission of the U^{235} nucleus. The neutrons produced in fission make the chain reaction possible, and are highly important in producing various radioisotopes and in fundamental research.

We shall soon be examining how the chain reaction, which enables the process of fission to be multiplied manyfold, is accomplished, and we shall see that, in spite of the complexity of the chain reaction as it occurs in a great variety of nuclear reactors, the fundamental products are still energy, fission fragments, and neutrons. Before pressing further into the uses of fission, however, we now turn to a process that in many ways is its reverse, even though energy evolution is also its aim—the now widely discussed process of fusion.

Fusion

The basic facts of nuclear structure that we have been considering, together with the principle of the conversion of mass into energy, will enable us to understand rather easily the process of *fusion.* In principle it can result in the release of extensive nuclear energy, as does fission, but it differs greatly in its basic mechanism.

In the process of fission, we have seen that the resulting fragments weigh less than the original uranium nucleus plus a neutron and that the mass that thus disappears reappears as energy, in an amount given by Einstein's equation.

In any nuclear transformation, in fact, energy will be evolved if the mass of the products after is less than that before the reaction. The extremely heavy elements, such as uranium and plutonium, are heavier than the atoms into which they split in fission, hence this process is always accompanied by a release of energy, because there is a *decrease* in mass. If the lightest elements, however, such as hydrogen and lithium, are formed by the splitting of larger atoms, the total mass would have to *increase* in the reaction. If helium, for instance, were to be split into two atoms of heavy hydrogen, that is, deuterium, each containing one neutron and one proton, it would be necessary to *add* energy in the process, because two deuterium atoms weigh more than one helium atom. If we desire, on the other hand, to *gain* energy from reactions with light atoms it is necessary to carry on the reverse process, that is, to combine the light atoms or to *fuse* them, instead of forming them by fission.

The process of fusion is thus one in which very light atoms are combined to make a larger atom, but one weighing less than the combined weight of the light atoms. Actually the amount of energy released when light atoms are fused in this way is greater for a given weight of material than for the heavier atoms, for which fission is the mode of energy release. Thus when two deuterium nuclei (deuterons) are fused to form a helium nucleus, that is, an alpha particle, 24 million electron volts of energy are released (Fig. 10). This sounds much less than the 200 million electron volts released when a uranium nucleus undergoes fission, and it is, per nucleus. However, because the deuterons are so light compared to uranium (about 1 percent), the amount of energy released when 1 *pound* of heavy hydrogen is fused is about seven times as much as when 1 *pound* of uranium undergoes fission. Even though the energy released in fusion and in fission comes from the disappearance of mass in both cases, the actual mechanism for attaining the nuclear transformation is markedly different for the two reactions. The basic reason for the difference in mechanism, which makes the attainment of the fusion reaction extremely difficult, is a rather simple one. It follows from the fact that the neutron, having no electric charge, can penetrate through the electric field surrounding the uranium nucleus, enter it easily, and cause fission to occur. If we are attempting to fuse the nuclei of two hydrogen atoms, on the other hand, the process is extremely difficult, simply because each nucleus carries an electric charge. As two electrically charged objects of the same sign repel each other, it is necessary to push the two hydrogen nuclei violently together, overcoming the electrical repulsion, before they can fuse. Incidentally, we can neglect the effect of the electrons that circulate around the nuclei in these considerations; in such violent motions they would certainly be stripped off the nuclei.

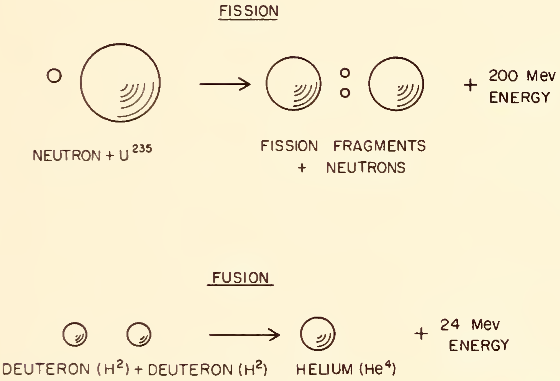


Fig. 10. The fundamental mechanism of the fusion reaction as compared to fission.

The only practical method for pushing the hydrogen atoms together violently enough is to set them in rapid motion. In turn, the only way to set large numbers of atoms in rapid motion is to heat them, and reactions of this type are called *thermonuclear,* that is, reactions produced by *thermal* or heat motions of the atoms. The heating required, however, is of no ordinary magnitude; in fact, temperatures of the order of 10 to 100 million degrees are called for to attain practical reaction rates. These temperatures are so much higher than any known in normal processes that it is difficult to envisage any method for their attainment. Even the temperature of the surface of the sun is only 10,000 degrees Fahrenheit, hence much too low for thermonuclear or fusion reactions to take place. The temperature inside the sun of course is much higher, well over 1,000,000 degrees, and it is almost certain that the energy radiated by the sun comes from thermonuclear reactions in the sun's interior.

There is a single known way at present in which the extremely high temperatures needed for thermonuclear reactions have been attained on earth; this is the explosion of the atomic bomb. We are here not concerned with the detailed mechanisms of bomb explosions but the hydrogen bomb illustrates very well the principle of fusion reactions. The H-bomb, in which the thermonuclear reaction takes place, reaches the necessary high temperature by means of an atomic or fission bomb, which by exploding heats the H-bomb material and thus triggers the fusion reaction.

At the present time our aim is merely to utilize the fundamental facts of nuclear structure and energy release that we have just learned in order to explain the fundamentals of the fusion reaction. After we have considered the practical methods for release of energy by fission and its many applications, we shall consider briefly the practical methods being used in an attempt to release fusion energy under control, that is, nonexplosively. This problem, whose solution unfortunately still lies in the future, will be the subject of Chapter 9. It is properly placed after all other considerations of peacetime atomic energy, because its very remoteness implies that it should not confuse our considerations of the present reality of atomic energy from fission, but should be relegated definitely to the future.

CHAPTER 3

THE CHAIN REACTION

ON DECEMBER 2, 1942
MAN ACHIEVED HERE
THE FIRST SELF-SUSTAINING CHAIN REACTION
AND THEREBY INITIATED THE
CONTROLLED RELEASE OF NUCLEAR ENERGY
—PLAQUE AT FOOTBALL STADIUM,
UNIVERSITY OF CHICAGO

We have now seen how it is that the change of one element into another is a deep-seated change, involving the transformation of nuclei themselves rather than the simple change in the outer electrons of atoms that characterizes chemical changes. The nuclear changes produce or require large amounts of energy relative to chemical, or atomic, reactions. Typical energies involved in nuclear transformation are about a million times as large as those in chemical transformations, because they involve the conversion of matter itself into energy or vice versa. In one particular nuclear change, fission, the energy evolution is higher still, about one hundred times that in the usual nuclear reaction. Whether a particular nuclear transformation is one that emits energy, or one that requires the absorption of energy to promote it, is simply a matter of the mass of the interacting particles before and after the transformation. When the final products are lighter than the initial ones, matter has disappeared and in its place energy, in an amount given by the Einstein equation, must necessarily appear.

The Need for a Nuclear Chain Reaction

Nuclear transformations are typically difficult to produce, however. Even though tremendous energy is involved *per atom* that undergoes a transformation, the production of macroscopic amounts of energy, that is, the transformation of an appreciable fraction of the atoms in a piece of matter, is an extremely difficult operation. When a beam of bombarding particles, such as those produced in cyclotrons, is sent through matter, the chance of hitting the nucleus of an atom, which is necessary to cause a transformation, is very small. The fundamental problem is how to get a sizable fraction of the atoms to transform.

It is thus clear to us, as it was to scientists in the early 1930's, that some development was needed, some invention that would cause the transformations of nuclei to spread through a mass of material. The transformation of a particular nucleus must not only give energy, but in some way cause other nuclei to transform in turn. This type of transformation, which could spread from atom to atom, was already a familiar concept in the field of chemistry, where the type of chemical change that could spread through material had already come to be called a *chain reaction.*

A chain reaction that propagates chemical reactions is based on some type of interaction wherein several atoms would form, change, or decompose a chemical combination with the evolution of a small amount of energy. If the particular reaction, in addition to giving energy, could in some way impart a triggering mechanism to nearby atoms, causing them to interact in the same way, then it is possible that the reaction could spread. If the spread is sufficiently rapid there could be a quick increase in intensity, resulting in the evolution of a large amount of energy from the initial transformation of a few atoms.

A dramatic illustration of this type of spreading of a reaction, or the chemical chain reaction, is the chemical change that takes place in the detonation of a high explosive. Here the first atoms that interact produce heat, which in turn increases the energy of agitation of other atoms, thus making the likelihood of chemical interaction between them much greater. The likelihood increases simply because the atoms meet others more often, and hence have a much greater chance of reacting. In this way the wave of reaction spreads so rapidly throughout the material that an intense explosion is produced.

The Fission Chain Reaction

With regard to nuclear transformations, the same kind of chain reaction would have been possible if some reaction had been known in which the nuclear energy could be evolved in such a way that it would cause further nuclear transformations. Although in principle a *nuclear chain reaction* might appear simple, for many years no nuclear reactions were known that had the needed self-propagating property. In spite of diligent search, there seemed no possible way to go from the stage in which only a tiny fraction of the nuclei could be transformed to one of a self-propagating reaction in which the inherently tremendous energies locked in the nucleus could be released on a practical scale.

However, just when the possibility of release of nuclear energy seemed extremely remote, the reaction of fission—which was completely unexpected—was discovered. Fission provided exactly the mechanism that was needed to propagate the reaction. In fact, as soon as the discovery of fission was made known, it was obvious to scientists throughout the world that the triggering mechanism for a nuclear chain reaction, with all its potent possibilities, was at last at hand. While it was not obvious that many practical obstacles could be overcome, the chances for eventual success had been increased manyfold.

The simple properties of fission that we have already learned show why it has the unique characteristics necessary to trigger a chain reaction. One neutron being absorbed by a uranium nucleus produces a large amount, 200 million electron volts, of energy and —of tremendous significance—causes the emission of several neutrons as the fission is taking place. "In principle," then, that is, in the happy state where we can forget about practical difficulties, we start with one neutron and no free energy and after fission of a uranium nucleus have a large amount of energy and about two or three neutrons.

Of course, as neutrons are the very missiles used to produce fission, the extremely self-propagating nature of the process is apparent—the number of neutrons is increased several hundred percent by the very process in which only one of them is consumed to produce the desired reaction. Thus, "in principle" the process of getting the self-propagating reaction of large magnitude seems ridiculously simple, but of course "in practice" we unfortunately must face all the practical difficulties.

Before considering the practical matters, however, matters which necessitated three years of hard work before the discovery of fission was followed by the successful chain reaction, it seems worth while to consider in a somewhat ideal way the simple properties of chain reactions. It is these simple mathematical properties of the chain reaction, independent of the actual physical details and practical difficulties, that made the prospect of a successful chain reaction seem almost too good to be true. As an illustration of the awesome nature of these first glimpses of the possibilities, it is interesting to recall that the argument was advanced by some scientists in the early days that the chain reaction would be impossible. They reached this conclusion on the basis that if it really were possible it would have already taken place naturally *somewhere* in the earth's surface, with disastrous results. To these people it just didn't seem possible that the large-scale release of nuclear energy, so tremendous in comprehension, could be accomplished by the limited efforts of men.

Simple Mathematics of the Chain Reaction

In order to examine the basic properties of the chain reaction and thus realize the immensity of its potentialities let us put ourselves in the place of the scientists who, immediately after the discovery of fission, were contemplating its role as the producer of the chain reaction. Thus we shall not be bothered by detailed practical difficulties at the moment, which is fortunate, for there are indeed many, but instead can examine how "in principle" the ideal chain reaction would operate.

Because of the ideal nature of our experiment, we can assume quite freely that we have a sufficiently large amount of pure U^{235} isotope, not stating at the moment how large is "sufficiently large." As scientists always do in situations similar to our present one, we now make some "simplifying assumptions" so that our mathematics can be expressed in uncomplicated form. For example, we know that when a uranium nucleus fissions it may emit one, two, three, four, or even more neutrons—the *average* number being 2.5. However, for simplicity, we shall make the assumption for the present that in our mass of U^{235} every fission produces exactly three neutrons; the *principles* of the chain reaction will not be altered thereby, and we need not be bothered with fractions. We shall also assume for convenience that each neutron produced travels through the mass of uranium until it is finally absorbed by a uranium nucleus, the probability of any other fate for the neutron being considered negligible, and the amount of U^{235} so large that neutrons produced in fission cannot escape without hitting a uranium nucleus.

Under our simplifying assumptions, it is an easy matter to trace the rapid course of a chain reaction in uranium from the stage at which only a few atoms are being split to one where actual large-scale release of energy takes place. In order to start the chain reaction in our assumed large mass of pure U^{235}, it is necessary somehow to produce at least one neutron in the mass. These neutrons could be produced by some external neutron source, such as a cyclotron, but this complication is actually unnecessary. Neutrons are ever present in all material, for example, as a result of *cosmic rays* that enter the earth's atmosphere from outer space and produce neutrons over the entire surface of the earth. In addition, neutrons are continually released from matter by the alpha rays produced by spontaneous disintegration of heavy atoms, or are the direct result of *spontaneous* fission, which occurs at a slow rate in U^{235} even without neutron absorption.

Thus neutrons would be present in the large amount of U^{235} that we are visualizing, with no effort on our part, and one of these would soon enter the nucleus of a U^{235} atom, fission would ensue, and the chain reaction would begin. In accord with our simplifying assumptions, three neutrons would then emerge from this fissioning nucleus, proceed until each of them had entered the nucleus of another U^{235} atom, and there produce fission. As a result of the three fissions that would then occur, nine neutrons would result, and the situation at this stage is pictured in Fig. 11. Immediately afterward these neutrons would enter nuclei and the nine fissions produced would give us 27 neutrons.

The numbers we are now considering, at the infant stage of the chain reaction, are still extremely small compared with the truly immense number of U^{235} atoms present in our sample. Thus the chain reaction is still only a tiny disturbance and it cannot be significant until it affects numbers that are comparable to the number of U^{235} atoms present. But before we allow the numbers to become so large, let us dwell on some of the mathematical principles that are already appearing in this continued multiplication by three. Here we are utilizing another characteristic of scientific "explanation," that is, the technique of proceeding by analogy. The analogy used for the chain reaction is a human population, and the terms actually used, even in the highest-level technical discussion of chain reactions, are just those terms that are characteristic of population growth.

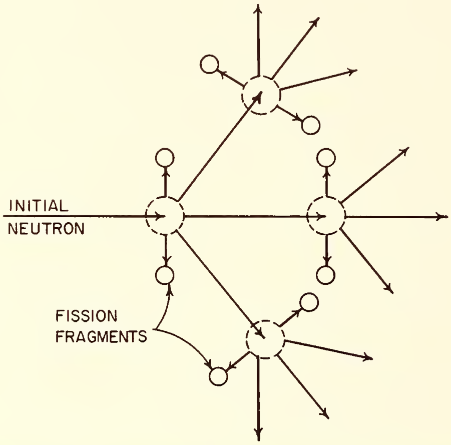


Fig. 11. The beginning of an idealized chain reaction in which three neutrons are emitted at each fission.

In the present case, using the accepted terminology, we would say that there is one neutron in the first *generation,* three in the second generation, nine in the third, and so on. A matter of great importance is obviously the length of time between fissions, that is, the time for each generation, and, as one would expect, it is called the *neutron lifetime* or *generation time.* If the generation time were very long, of the order of a minute, for example, we would have to wait an extremely long time to get significant numbers, and a rapid chain reaction would be impossible. However, the actual generation time is extremely short, being just the time it takes on the average for a neutron to move from the atom where it is created to the atom where it is absorbed.

As we know, the neutron must proceed through billions of uranium atoms before causing a fission, for that process requires a collision with a nucleus, the neutron usually passing through the outer regions only of each atom on the way. Although billions of atoms must be passed before a fission results, the time required to pass all these atoms is nevertheless extremely short. A neutron produced in fission has an energy of about 1 million electron volts, incidentally representing only a tiny fraction of the total energy released in fission, most of which appears as kinetic energy of the fission fragments. The neutron speed, however, is still great, being about 5 percent that of the velocity of light, or in other units, over 8000 miles per second. At such high speeds it is not surprising that the time required for the neutron to move a few inches, which is necessary before it is absorbed by a nucleus, is only of the order of a few billionths of a second.

It is this extremely short generation time, about a billionth of a second, that carries us in an incredibly short period from the microscopic stage at which a few atoms are being split to the macroscopic stage at which we measure energy release in terms of tons of TNT or kilowatt hours rather than numbers of individual atoms. In the final condition, the number of atoms being split at a given time is tremendous compared to the few with which we start, being billions and billions of fissioning nuclei instead of a few. However, we can easily show that the time required to reach this macroscopic, perhaps explosive, state is still short.

If we continued to multiply by three we would become tired long before we reach the numbers necessary for large energy releases. Fortunately, we can avoid the tiresome process, for to find the result of continually multiplying by the same number is an extremely simple mathematical problem and we can easily predict what it will be at any particular time. When a quantity is multiplied regularly by a given number, the result is known as an *exponential function,* and the solution can be found easily in standard mathematical tables or even more easily can be constructed graphically, as we shall illustrate. The simplest example of an exponential function, and one most familiar to us, is the regular multiplication of a principal that is represented by interest compounded regularly. The process is exactly the same as the chain reaction but, unfortunately, much, much slower in its rate of growth. Thus

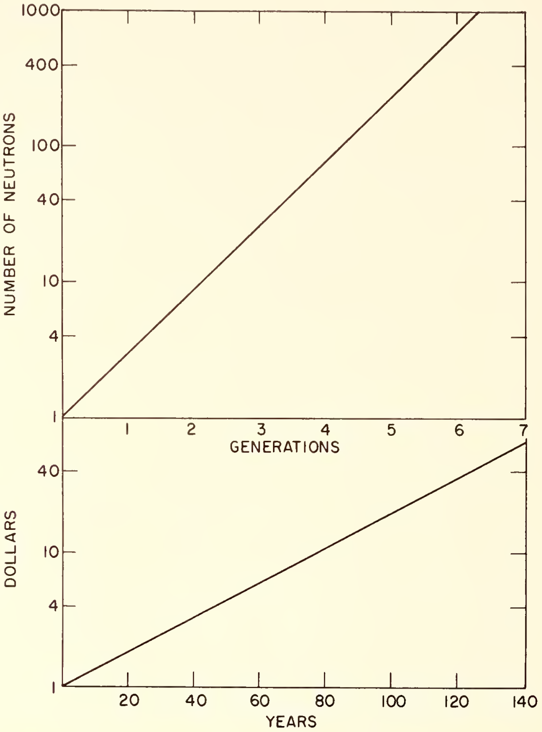


Fig. 12. Two examples of exponential curves: upper, for the chain reaction; lower, for 3-percent compound interest. Such exponential increases appear as straight lines when the vertical scale is logarithmic, as in this figure.

money earning 3 percent interest compounded annually represents a multiplication by 1.03 once a year. Here $1.00 becomes at yearly intervals, $1.03, $1.06, $1.09, and so on. Even this slow increase becomes very rapid after a very long time, for 500 years later the principal increases in the next year by about $80,000 instead of the initial 3 cents.

In our case of the chain reaction, however, instead of multiplying by 1.03 we multiply by 3, and instead of a yearly rate, multiplication occurs each billionth of a second. In other words, it is an interest rate of 300 percent compounded every billionth of a second! The resulting increase in our principal (of neutrons) is best shown by a graph, as in Fig. 12. In this figure it is noted that the numbers along the vertical direction, representing the principal, appear on what is known as a *logarithmic scale,* which differs greatly from the usual uniform scale. The effect of this scale, however, is very useful, in that a straight line on the figure represents just the type of increase that is obtained with regular, repeated multiplication, that is, the exponential behavior.

A slow rate of increase, represented by the 3-percent interest per year, is shown in the lower part of Fig. 12; here it is seen that the rate of increase remains small for many years. It is clear from the upper curve of Fig. 12, depicting the chain reaction, that in an extremely short time the number of neutrons grows tremendously. Actually, in about 7 billionths of a second the neutron population increases a thousandfold. Thus it is easy to appreciate how in extremely short times macroscopic amounts of energy are being released, thousands of kilowatt hours rather than the energy from a few splitting atoms. The problem then is not one of waiting for the chain reaction to get going, but, having attained the conditions for its propagation, to keep it from running violently away as an explosion!

The Practical Difficulties

The enormous possibilities inherent in the release of nuclear energy that we have just sketched aroused great enthusiasm on the part of some scientists even though the practical difficulties, which we have neglected so far, were enormous as well. To the more cautious, however, the difficulties seemed insurmountable and some even felt that neither the explosive chain reaction nor the controlled peacetime variety could ever be attained. Actually, the enormous magnitude of the program necessary for production of a practical chain reaction might well have deterred serious effort for decades, had it not been for the lavish technical support of a war economy. One simple argument advanced by the pessimists at the time, as already mentioned, was that a chain reaction, if possible, would already have occurred in nature at some time when the right combination of uranium and neutrons had occurred by chance.

An important point concerning this pessimistic argument is that it could be applied only to the type of chain reaction that would occur in *natural uranium,* which is composed mainly of U^{238}. It was realized that the chain reaction would be much more possible if the isotopes of uranium were separated and only pure U^{235}, the more fissionable isotope, were used. Separation of isotopes on a practical scale, for example, to produce pounds of material, had not been accomplished at the time, and this in itself would obviously be a vast industrial project. Fission is possible for neutrons of all speeds in U^{235}, unlike U^{238}, where only the most energetic neutrons can cause fission to take place. Even for the pure U^{235} isotope, however, it was not at all obvious that the chain reaction could be produced in a useful, practical manner. In order to examine the difficulties involved in the attainment of the chain reaction, let us first consider how it would operate in pure U^{235}, leaving aside for the moment the more difficult problem of chain reactions in natural uranium.

Anything that we describe about the chain reaction in U^{235} applies equally to Pu^{239}, the other important fissionable nucleus, an isotope of the element *plutonium.* This isotope was completely unavailable, however, when chain reactions were first being studied, for plutonium was actually manufactured by the chain reaction when it was finally attained.

In considering the chain reaction in pure U^{235}, let us first imagine an experiment in which we are studying fission induced by neutrons in a piece of the isotope U^{235}. This would certainly be a small piece of U^{235}, especially if the experiment were done in the early days of atomic energy, for the great difficulty of separating isotopes would mean that only small amounts of U^{235} would be available. So let us imagine we are shooting neutrons into a piece of U^{235} about the size of a marble, which amount would have been available, but practically no more, about 1944. Incidentally, as we can predict from what we already know about isotopes, this bit of U^{235} would exactly resemble normal uranium metal, which is mainly U^{238}. As far as any properties based on atomic behavior, such as hardness, appearance, chemical reactions, and so on, are concerned, it could not be distinguished from normal uranium metal. As far as *nuclear* behavior is concerned, vital differences exist, but all the atomic properties reside in the outer electron structure, which is identical for U^{235} and U^{238}, both having 92 electrons.

If the experiment were being done in a well-equipped laboratory, we would no doubt have some source of neutrons with which to bombard our piece of uranium metal. In our imaginary experiment, however, we can dispense with an imaginary neutron source, for sufficient neutrons would be flying through the room that an appreciable number would cause fission in the lump of uranium every second.

So let us look more closely at one of the uranium atoms whose nucleus has just undergone fission. From the rapidly separating fission fragments, several fast neutrons will be produced, let us say three. These neutrons will move through the small solid block of U^{235} metal with little to impede them, for, being electrically uncharged and hence unaffected by the electrons, they move freely through the outer regions of the uranium atoms. The nucleus is so small that the chance of one of the neutrons colliding with it while traveling through an atom is extremely small. As a result, the neutrons move several inches, passing through billions of atoms in the process, before their chance of being absorbed by a nucleus becomes appreciable. As our lump of uranium is so small, however, the most likely occurrence is that the three neutrons will not be absorbed but will escape from it without causing further fission. In technical atomic-energy terms we would say that the *leakage* is so large that the chain reaction would not be *sustained.*

Further fissions would take place when other neutrons entered the uranium lump from the outside, any given incident neutron of course having only a small chance of causing a fission. However, the important point is that there would be no *multiplication,* the $3 \times 3 \times 3$ process that we have discussed "in principle." Because of the large leakage a neutron of one generation has only a small chance of producing another generation at all. Mathematically, the present case is taken care of by multiplying by a small number, rather than by 3; in fact, for our U^{235} lump this number, which gives the probability of a neutron in one generation producing another in the next, is about 0.1. Continued multiplication by 0.1, however, soon gives a negligibly small result.

The Critical Size

It is fairly obvious what must be done in order to decrease the neutron leakage and thus increase the chance of attainment of the chain reaction; we must pile more U^{235} around our original lump to prevent the escape of the neutrons. We have mentioned that fast neutrons move several inches through solid uranium before their chance of hitting a nucleus becomes large. It is evident then that if, instead of a piece of U^{235} the size of a marble, we make our lump the size of a basketball, the chance of neutron leakage will be very small. In the case of the large uranium lump, provided that other fates do not await the neutron, it will most likely not escape but will be absorbed by another uranium nucleus and give rise to the emission of three more neutrons.

Thus for this large amount of U^{235}, if we neglect the leakage completely, the mathematics that we have recently discussed, and illustrated in Fig. 12, would apply. Our imaginary experiment would almost immediately be an extremely explosive one, for now any neutron entering the lump would start the rapid neutron multiplication, the $3 \times 3 \times 3$ of Fig. 12. The energy release that would result from the tremendous number of fissions so quickly developed would be of explosive violence. In short, we would have in effect the explosion of a gigantic bomb.

Actually, somewhere between the extremes of the marble-sized lump and the basketball, between the extremes of essentially nothing happening and a tremendous explosion, there must be some size where things are happening, yet are relatively controllable. It is almost immediately obvious that we could not actually accomplish the experiment just described with the large-sized U^{235} mass, for it would be impossible to assemble—it would explode as the assembly was being performed. These conclusions are actually the key to the whole situation, for it is indeed true that there is a certain *critical size* or *critical amount* of U^{235} that will just sustain the chain reaction.

An amount of U^{235} less than the critical size is completely stable and completely harmless. Fissions do take place in this *subcritical amount* and the neutrons thereby produced sometimes do cause further fissions. However, the number of neutrons in one generation, for such a mass, is always less than the number of their progenitors of a previous generation. In other words, instead of multiplying, say 3 × 3 × 3, we would be multiplying by a number less than one, say 0.9, hence the neutron population would decrease generation by generation, with some possibility, of course, of being replenished by fresh neutrons from outside sources.

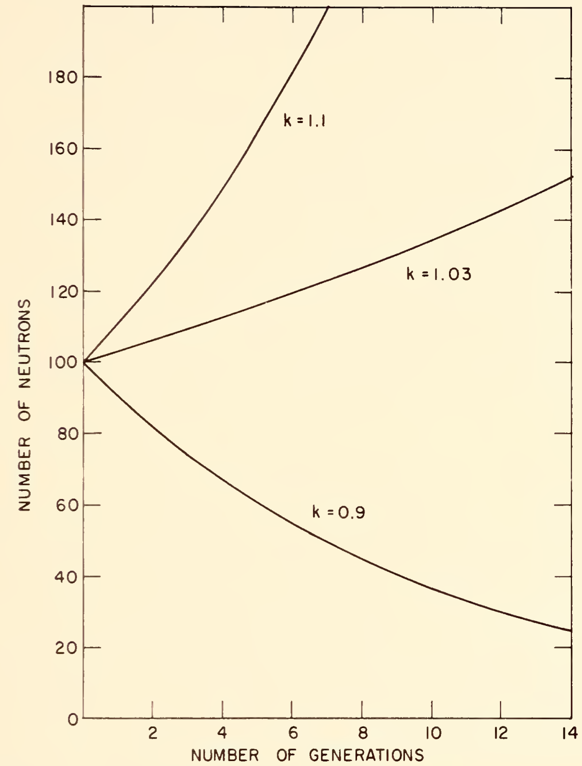


Fig. 13. The changes with time for chain reactions with the reproduction factor *k* slightly greater than 1 and less than 1, for 100 incident neutrons.

An amount of uranium larger than the critical amount has a neutron population that increases with each generation. If the amount of uranium is barely larger than the critical size, the number by which we multiply may be only slightly greater than one—perhaps even 1.03, to bring out the analogy with a rate of interest. In that case the number of neutrons would surely increase, but slowly, so slowly that no explosion would result. We should be careful to note that the increase is slow because the multiplier is close to unity, not that the *generation time* is any different, for it remains the same, regardless of the amount of U^{235} present. The course of events in amounts of U^{235} above and below critical is sketched in Fig. 13.

The exact value of the critical amount of uranium is still a classified matter, but officially published information of the Atomic Energy Commission has stated that the critical amount is larger than a golf ball but smaller than a basketball. The size can almost be estimated without much difficulty from the fact that, as we have already said, the fast neutron moves several inches before being absorbed. It is this dimension that determines the dimension of the material necessary to prevent the escape of neutrons, hence the critical amount.

The Atomic Bomb

Because the multiplication of neutrons can be made more or less rapid, depending on the size of the uranium lump, it is possible to produce a chain reaction that is mild or one that is of great explosive violence. It is a matter simply of adjusting the number by which we multiply the neutron population in each generation, keeping it somewhere in the range from 1 to 3. Here we might as well begin to use the correct technical term for this multiplicative factor, and save ourselves many words. By analogy with a human population, it is called the *reproduction factor.* If the reproduction factor is slightly less than one because the lump is just below critical, we would have no chain reaction. The number of neutrons in the lump, and escaping from it, would be rather large because many of the neutrons emitted during fission would cause further fissions and the emissions of more neutrons. But the net number produced in each generation would be somewhat less than the number in the preceding one that had produced them, as we show in Fig. 13.

If we then add a slight amount of uranium to the lump, enough to cause the reproduction factor to be slightly greater than one, we would notice that the number of neutrons coming from the lump would increase very slowly with time, as in Fig. 13. The intensity could be an even more slowly increasing exponential function, changing by much less than 1 percent each generation in an amount of U^{235} carefully adjusted to be just larger than critical. And there would be ample opportunity to remove the added pieces before the intensity became dangerously high.

In the other extreme, should we make our lump so large that the reproduction factor is about two, then the multiplication would be so rapid that an explosion would result. Of course the immediate question is, how do we get the lump so large that the reproduction factor becomes two without having it explode in the process? We cannot say, "simply exclude neutrons from entering the lump during the process," because some of the uranium atoms undergo *spontaneous fission,* which is fission that occurs without absorption of a neutron. Neutrons are constantly being produced from spontaneous fission, so we cannot keep neutrons out of our lump of U^{235} while we assemble it.

The only answer is to assemble the pieces so rapidly that they get together before they are blown apart by the force of the explosion. In that case our experiment really becomes one in which we are exploding an *atomic bomb;* in fact, this rapid assembly is exactly the process by which an atomic bomb is detonated. The atomic bomb is simply an amount of U^{235} (or Pu^{239}) larger than the critical amount, that is, a supercritical mass, which is kept in separated pieces, then assembled as rapidly as possible when the detonation is desired. The detailed method of assembly is still a matter of military secrecy, but the principle of the process is that the uranium pieces are suddenly slammed together into a compact mass, attaining the highest possible density in the process, the slamming being accomplished by the force of high explosives. The *efficiency* of the explosion, that is, the fraction of the uranium that undergoes fission before the whole thing is blown apart, is greatly dependent on the exact method by which the parts are slammed together and the density that is attained in this rapid assembly. Of course, even under the best conditions, all of the uranium does not undergo fission in an atomic bomb, and intense research is devoted to improving the efficiency of the methods of detonation.

The Controlled Chain Reaction

It is not our purpose to consider atomic bombs, their detonation methods, delivery, and effects in this book, although in Chapter 8 we shall discuss the vital matter of the danger of radioactive *fallout* resulting from their explosion. We have used the atomic bomb merely to illustrate one extremity of the range of possible chain reactions—the one that releases nuclear forces with uncontrolled violence. With somewhat less uranium, however, for which the intensity of the chain reaction can easily be regulated by adding and taking away bits of uranium, we would have a *controlled chain reaction.* True, it would hardly be a form adapted to practical, useful purposes, such as the production of power. But our lump of U^{235} has illustrated for us the principle of the *reproduction factor* and has shown why a certain critical amount of uranium will support the chain reaction whereas a slightly smaller amount is completely stable.

An important principle that we have not mentioned specifically but which follows directly from our discussion is that the *power level* at which the chain reaction operates is not a matter of how large the amount of uranium may be but simply how long the multiplication has continued. Even if the amount of uranium is only ever so slightly greater than critical, the power level, that is, the number of fissions taking place at a given time or the rate of heat production, can reach any arbitrary value. It is simply a matter of allowing the multiplication to take place for a sufficiently long time. The rate at which the power level rises, given by the exponential curves of Fig. 13, will of course vary with the amount of uranium, but the ultimate level reached will not. In fact, any power level can be attained, in principle, if we are willing to wait long enough.

Of course it is not only necessary to wait long enough (the reason we included the "in principle") but to take the heat energy out of the lump of U^{235} to prevent it from melting. It is also necessary to protect ourselves in some way from the very large number of neutrons and the radiations from radioactive atoms from the chain reaction. In other words, for an intense chain reaction, the three products—heat, radioactive fission fragments, and neutrons—are always present, and create serious practical problems in their handling.

Thus many things must be done in a practical way before our simple chain reactor, hand-built of U^{235} blocks, can be applied to useful purposes. Actually our experiment, which we have presented as if it were pure imagination, is an accurate description of the type that was carried out many times during the war years. Small blocks of U^{235} or plutonium (Pu^{239}) were piled up slowly, just as we have described, until the critical point was reached, the intensity of the chain reaction being kept so low that no harmful results would be produced. The adjustment of the reaction rate was made merely by moving the last piece near the large pile of fissionable material. The balance of neutron production and loss is so delicate that for a lump near the critical size the final adjustment of the reproduction factor could be accomplished simply by holding one's hand near the uranium or plutonium structure. The reason is that the number of *leakage* neutrons *reflected* or scattered back into the lump from the hand are enough to make the reproduction factor go above unity for a configuration just below critical. Thus the intensity of the chain reaction, as measured by radiation recorded on a Geiger counter, could be regulated literally by a wave of the hand.

A tragic note in this connection, and an illustration of the sensitivity of the chain reaction to the reproduction factor, is that twice at Los Alamos, during such experiments, fatal mistakes were made. The mistakes were simple ones—the last piece approached the mass too quickly—but the results were far from trivial. The reaction multiplied with fantastic speed, and, although no explosion took place, the radiation, consisting of neutrons and beta and gamma rays, was so intense that following each of the two mishaps one scientist died from overexposure to radiation.

The purpose of these experiments with hand-built chain reactors was to determine, by actual attainment of critical conditions, the purity of the fissionable material, U^{235} or Pu^{239}. Because certain chemical elements have a great affinity for neutrons and thus steal them from the chain reaction if present, it is important that the fissionable material be very pure in order to attain the chain reaction with the minimum amount of material. The so-called *critical experiments* being carried out at Los Alamos were done simply for this purpose, to measure the purity of U^{235} or Pu^{239}, destined for use as bombs, by determining the exact amount necessary to attain the chain reaction, or, as it is said technically, to reach *criticality.*

The First Nuclear Reactor—The "Pile"

The hand-built chain reactors we have just described are hardly practical because the heat energy cannot be removed from them nor is there any protection from radiations. In addition, there are other compelling reasons why this type of structure is not appropriate for a practical controlled chain reaction. Important as are the matters of protection from radiation and removal of heat, a much more important objection to the type of reaction just discussed is that it utilizes U^{235}, which, being a separated isotope, is very difficult to produce. For this reason, another type of controlled chain reaction was the main concern during the years of the war—one that could take place with normal uranium, thus avoiding the extremely difficult process of separating the U^{235} and U^{238} isotopes. It is a dramatic story in itself, but one that we unfortunately cannot take time to describe in great detail—the story of the way in which, during the years 1940, 1941, and 1942, scientists strove diligently to find some way by which the reproduction factor could be made larger than unity in unseparated or *natural uranium.*

It soon became clear that natural uranium by itself, that is, in the form of metal, had a reproduction factor definitely less than unity even if completely free of impurities. However, the early experiments and calculations showed that other materials, when combined with uranium in the proper way, could actually increase the reproduction factor. The great quest then was for some combination of materials that might give a controlled reaction with normal uranium, even though its U^{235} content is less than 1 percent.

Actually, even though we have *described* the chain reaction for pure U^{235} in the interests of simplicity, the first controlled chain reaction actually *produced,* in December 1942, utilized natural uranium. It would have been much easier to attain the first chain reaction with the pure isotopes U^{235} or Pu^{239}, but they were not available in 1942. The first explosive chain reaction, the atomic bomb, using pure U^{235}, was not attained until 1945, but the reason for this three-year interval is simply that it required the additional time to separate enough U^{235} from U^{238} to make the atomic bomb. The natural-uranium chain reaction attained in 1942 took place in the world's first *atomic pile,* or, as it would now be called, the first *nuclear reactor.*

The device in which the first controlled nuclear chain reaction took place was called a *chain-reacting pile* simply because it was made by piling the material of which it was constructed on a flat space. The largest flat space that was available at the University of Chicago in 1942 was the floor of a squash court and here, under the direction of Enrico Fermi, the first nuclear chain reaction came into being. The structure was built by piling bricks of graphite, which is a common form of the element carbon, in regular layers and placing blocks of uranium metal several inches in size in the pile of graphite blocks. Figure 14 shows the appearance of the structure with several layers in place.

The idea behind this rather unusual combination of graphite blocks and uranium was extremely important, and basic to the successful attainment of atomic power. The nuclei of carbon atoms have the ability to reduce the velocity of neutrons that hit them but with very little probability of absorption of the neutrons. The low absorption is directly related to the structure of the carbon nucleus, which, consisting of three pairs of neutrons and three pairs of protons, is a very stable configuration. Thus the fast neutrons emitted from a uranium lump following fission are slowed down by the carbon nuclei, without being absorbed, until they are of the same energy as the carbon atoms themselves, a few hundredths of an electron volt.

Because of their specific properties the graphite atoms fulfill the dual purpose of hindering the escape of neutrons from the structure and, by slowing them down, of making their absorption in the uranium much more likely. Actually it is a general property, true for almost all materials, that neutrons are absorbed more and more readily as their velocity is decreased. A neutron in such a combination of uranium and graphite lives much longer than it would in the block of pure U^{235} that we have been discussing. Its *lifetime* in the pile is about a thousandth instead of a few billionths of a second, as it would be in pure U^{235}.

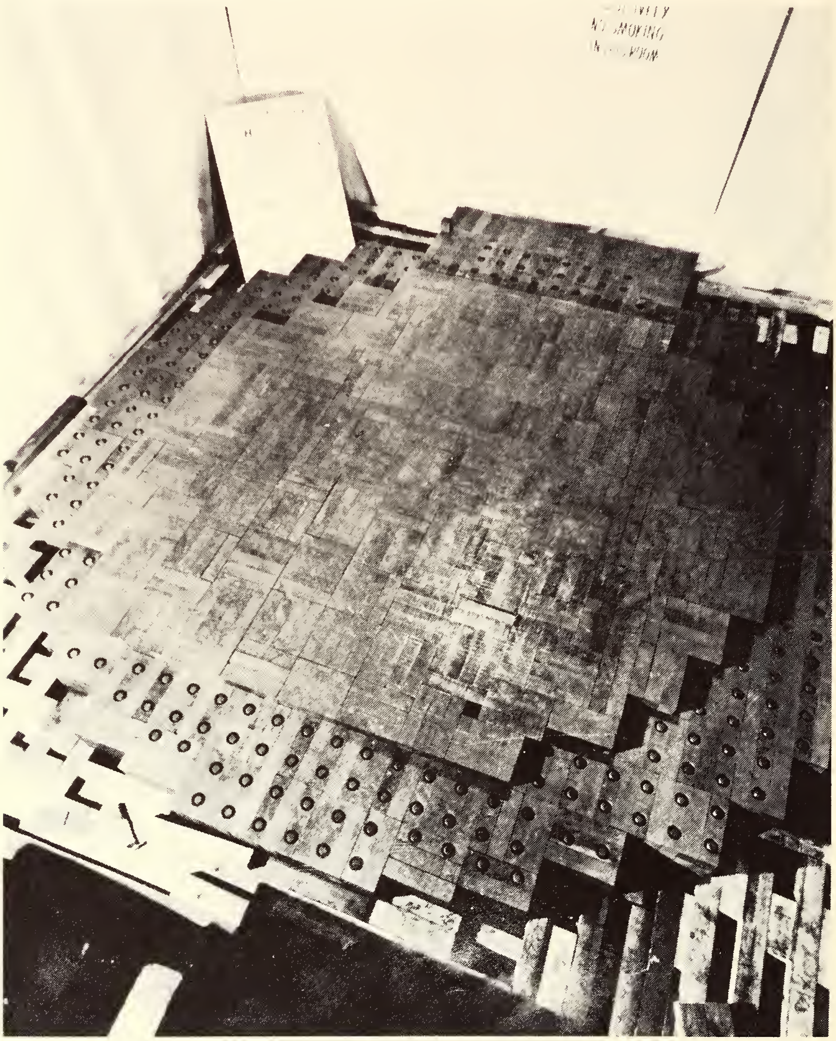


Fig. 14. The first chain-reacting pile, shown in the process of construction. The layers of graphite, containing holes in which lumps of uranium are placed, can be seen in the structure. (Courtesy of Argonne National Laboratory.)

There is a certain critical size for the pile of material, just as there was for pure U^{235} in our imaginary experiment. However, for the *natural uranium–graphite reactor* built in 1942 this critical size is something of the order of 15 feet instead of a few inches. An advantage of the large size of the structure is that it is very easy to regulate the size, hence to produce safely a reactor with a reproduction factor only slightly greater than unity. As a result the power level is easily controlled and the danger of an explosion extremely slight.

While the graphite blocks and uranium lumps of this first chain-reacting pile were being put in place, the neutron intensity, measured by suitable instruments, rose gradually until the chain reaction began when criticality was passed. At this point the reproduction factor was greater than unity by much less than 1 percent, hence there was no difficulty in stopping the chain reaction before it reached a dangerously high power level.

It was found possible to stop the chain reaction, that is, to reduce the reproduction factor to below unity, very simply, by pushing a long steel rod containing some boron into the structure. As boron nuclei have an extremely high affinity for neutrons, enough neutrons of each generation were absorbed to bring the reproduction factor below unity. It was found that the intensity or *power level* of the pile would drop very quickly after insertion of the rod, which is called a *control rod.* Also it was very easy to control the power level of the pile simply by moving the control rod. The longer the control rod was left out the higher the power or intensity of the pile would rise. The power could also be kept at any desired point, say 1 watt, 1,000 watts, or even higher powers, simply by appropriate motions of the control rod.

As this first chain-reacting pile was bare, that is, was not surrounded by a shield to stop the dangerous radiations emitted during fission, it was not safe to allow it to run at high power levels. The basic purpose of this first chain-reacting pile, however, had been successfully accomplished, even if it ran only at low intensity. It was not designed to produce intensely high power levels, but to demonstrate that the chain reaction was possible and to study some of its fundamental principles.

In actual fact, on the basis of the performance of this first chain-reacting pile, the very large well-shielded piles, or reactors, were immediately thereafter built at Hanford, Washington. These reactors, although operating at many millions of watts, were designed not to produce electrical power but to use the large numbers of neutrons to make the new element, plutonium, which is formed when U^{238} absorbs neutrons. The destined use of this plutonium was to make atomic bombs, the plutonium being just as useful for this purpose, and actually behaving almost the same, as U^{235}. As far as the principles of the chain reaction and atomic bombs are concerned, there is very little choice between U^{235} and Pu^{239}. In the next chapter we shall have occasion to return to the matter of the making of plutonium in a chain-reacting pile, because of the possible importance of Pu^{239} as a fuel for many applications of atomic energy to electric and motive power.

Nevertheless, the start-up of the first chain-reacting pile in December 1942, even though it was of low power and had no cooling facilities for removing heat and no shielding for protection, was an occasion of high drama, introducing atomic power to the world.

Simple Pile Theory

Before leaving this first chain-reacting pile it is well to spend some time examining some of the simple principles of its operation. At the present time so many widely different types of reactors are being designed that it is a bit bewildering to contemplate them and to try to recognize and understand the simple principles that operate in all the various types. Whether they are used to produce plutonium, power in an atomic submarine, electricity for a city, or radioisotopes for research, the same basic principles are still at work. So let us examine these principles as exemplified by the first simple natural uranium–graphite slow-neutron pile.

It is in a way rather strange that the natural-uranium pile should operate at all. We have already seen that ordinary uranium metal by itself will not support a chain reaction; it is only when the uranium is placed in lumps in a *moderator* such as graphite, with the lumps just the right distance apart, that the chain reaction can take place. Furthermore, it is only when the graphite and the uranium are purified to a fantastic extent that the chain reaction will operate. It was necessary for the graphite industry during the war to learn to make graphite of purity never conceived before. This purification was necessary to prevent the neutrons from being absorbed by the impurities in graphite, which would lower the reproduction factor below unity and make the chain reaction impossible of attainment. The same situation existed for the uranium metal itself and some impurities, such as boron, had to be kept so low that there was less than one atom of impurity per million uranium atoms.

A brief examination of the life history of a neutron, from the time it enters a uranium lump until one of its descendants enters another uranium lump, will serve to illustrate the delicate balance of the many factors that had to be adjusted in order to make the first successful chain reaction. When a slow neutron enters a lump of uranium and there dies by being absorbed, it *may* cause a fission (for other possibilities exist) and start the new generation with the production of several fission neutrons. We have been approximating the number as 3 for convenience, but now we propose to be much more exact; the exact number of neutrons produced *on the average* per fission is 2.50. Unfortunately, the incident neutron may die in other ways inside the uranium, for instance, by capture in the abundant isotope U^{238}, which process does not produce fission. Capture in U^{238} does produce plutonium (after two beta particles are emitted), but this process does not help the chain reaction. As a result of the competition for the neutron only 1.35 neutrons are produced in a uranium lump for each neutron absorbed in the lump, the reduction from the value 2.5 being caused by the competitive modes of capture of the neutron. The number 1.35 is the value of the important constant η, the Greek letter "eta," which is of great significance for natural-uranium reactors. It is defined simply as the average net number of neutrons produced when one neutron is absorbed in uranium. There is a slight increase in the number of neutrons as the fast fission neutrons leave the uranium lump, for some of them cause fission in the abundant U^{238} isotope; this effect increases the number of neutrons from a lump by about 5 percent (the *fast effect,* signified by the Greek letter "epsilon," ε, thus being 1.05).

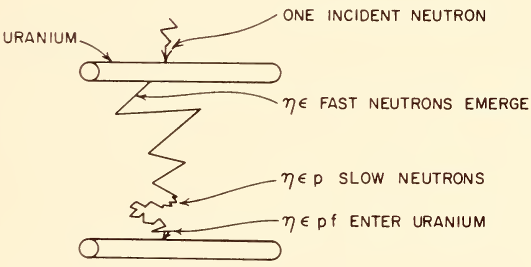
As the fast neutrons move through the graphite, collisions with the graphite nuclei cause them to lose energy rapidly. The value of this moderation of the neutrons is that their rate of interaction with matter, including uranium, is much greater when they are moving slowly. There is, however, the disadvantage that they may be captured by various atoms in an undesirable manner as they are slowed down. The most potent type of absorption is by the U^{238} nuclei, and it is to avoid this type of capture that the uranium is disposed in the form of lumps. The reason for the efficacy of the arrangement in lumps is that the capture by U^{238} is of a peculiar sort that takes place near the surface of a lump, but not throughout its volume. This effect on fast neutrons is very different from that on slow neutrons, which easily get through the surface layer. The chance that a neutron can be successfully slowed down and escape this *resonance capture* is about 87 percent and this factor, p, is called the *resonance escape probability*. Right here we see one advantage of the use of enriched uranium (containing more than the normal amount of U^{235}) in a reactor. In the case of pure U^{235}, for example, the value of p would be unity except for the small amount of absorption in structural material of the reactor, which fortunately can be made practically negligible by proper choice of materials.

At this stage of the neutron's life history we have $\eta\varepsilon p$ neutrons that have been successfully slowed down without capture for one original neutron absorbed in uranium. This product is well above unity ($1.35 \times 1.05 \times 0.87 = 1.23$), but unfortunately it does not give the reproduction factor as yet. The reason is that some of the slow neutrons may be absorbed by the graphite atoms and not reach the uranium lumps at all. The fraction of the slow neutrons that do reach the uranium is of the order of 85 percent, and this fraction is called the *thermal utilization factor* f. Thus we have finally for the value of the *reproduction factor*, always denoted by k,

$$k = \eta\varepsilon p f,$$

which for the constants we have given will be 1.23×0.85, or 1.05. Thus the reproduction constant is barely over unity even though extremely pure materials are used and the sizes and geometric arrangement of materials are carefully optimized. The neutron life history we have just described is recapitulated graphically in Fig. 15.

Thus far we have said nothing of the possibility that neutrons may escape from the reactor. The value for k of 1.05 would hold only for a reactor of infinite extent, for otherwise some neutrons would escape, thus lowering k. An actual reactor must be built so that no more than 5 percent of the neutrons can escape in order to have the chain reaction sustained; if the escape is exactly 5 percent the number of neutrons in a generation will be just the same as in the preceding generation. To keep the escape below 5 percent the reactor must be rather large, of the order of 15 feet across. This is the minimum size of reactor for pure materials; if a coolant and structural materials are included they will absorb neutrons and the leakage must be made even smaller, hence the reactor even larger. With such small values of *excess reactivity* (the excess of the reproduction factor over unity, or $k - 1$) it is very difficult to put in engineering features that would be otherwise desirable, such as strong structural materials and sufficient coolant to take out large amounts of power. It is for these reasons that the natural uranium–graphite pile has severe limitations as far as engineering features are concerned, and is always a very large structure.


ONE INCIDENT NEUTRON
URANIUM
$\eta\epsilon$ FAST NEUTRONS EMERGE
$\eta\epsilon p$ SLOW NEUTRONS
$\eta\epsilon pf$ ENTER URANIUM

REPRODUCTION FACTOR $k = \eta\epsilon pf$

Fig. 15. The life history of neutrons in a slow-neutron reactor.

Review of the Fundamentals of Controlled Chain Reactions

In this chapter we have learned much about the fundamental principles of the chain reaction, principles that apply whether the chain reaction takes place in a millionth of a second in pure U^{235} or Pu^{239}, and is thus an exploding atomic bomb, or occurs in a large graphite-uranium pile, with a reproduction constant barely over unity. Lest we lose the coherence of the entire picture, however, it is perhaps a good idea to remind ourselves again briefly of the basic happenings in the act of fission itself, for that process, continued indefinitely, *is* the chain reaction.

Fission is a particularly violent nuclear transformation in which matter itself disappears. The disappearing matter is replaced by energy in an amount given by Einstein's equation, and this energy appears as energy of motion of the separating fission fragments. In addition to the fragments, neutrons are produced during the act of fission, and these neutrons, essential to carrying on the chain reaction, represents a very intense source of radiation that can be used for many other purposes in the nuclear reactor itself as well as outside its shield.

As the fission fragments separate, their great instability or energy excess is revealed not only by their emission of neutrons but also by their emission of other types of radiation, that is, gamma rays and beta particles. As we have seen, gamma rays are short-wavelength rays similar to x-rays, whereas beta rays are simply electrons moving at high speed. The energy of motion of the fission fragments, because they are usually produced in solid matter, is soon turned into *heat energy* as the fission fragments bounce against the atoms of the material in which they are found, usually uranium metal. The energy of the random motion of the atoms of the uranium, which is increased by the collisions, is simply heat energy, and its increase is evidenced as a rise in temperature.

Thus as far as practical effects are concerned the three immediate consequences of the chain reaction are: (1) heat, (2) beta and gamma radiation, and (3) neutrons. These are the products of all chain reactions, whether they are operating in bombs or in nuclear reactors, and these are the products that mankind has available for his use, whether for destructive or for beneficial ends. A large amount of heat energy suddenly released produces an explosion, but large amounts of energy released in a controlled way and used to generate high-pressure steam can make almost unlimited quantities of electrical power. The radiations from the fission products, if present as fallout from a bomb explosion, can kill or cripple thousands, but the same radiations can be used for research, or even more directly for the treatment of cancer. The neutrons themselves in a bomb explosion are lethal, but the same neutrons released in a controlled way tell us many of the secrets of the interior structure of matter, or they can even be sent into the body to destroy malignant tissue.

These, then, are the principles of all chain reactions, and these principles, which we have covered in the last two chapters, will enable us to see in the succeeding chapters how the three products of chain reactions are already proving that atomic energy can be a potent tool for the advancement of mankind in the ways of peace. Heat, neutrons, and radiation are being used at an ever-increasing rate to further the general physical welfare of mankind. Perhaps an even greater potentiality rests in a broader realm, however, in the possibility that coöperation in the furthering of the physical benefits of atomic energy may lead to international understanding in the wider political sphere.

CHAPTER 4

ATOMIC POWER

In the long course of human history it seems to me that the truly great significance of nuclear energy will be as a source of useful heat and power. Its eventual importance to mankind in this regard can hardly be less than that of fire.

—A. H. COMPTON, *Atomic Quest*
(OXFORD UNIVERSITY PRESS, NEW YORK, 1956)

We have seen that three products result from any chain reaction—heat, radiation, and neutrons. Of these, the first has thus far received by far the greatest public notice, for it is the heat of a chain reaction that, converted to mechanical energy, drives the atomic submarines "Nautilus" and "Sea Wolf," that some day may propel airplanes and rockets, and that is already providing many thousands of kilowatts of electrical power. Unceasingly, since the first atomic bomb made the entire world aware of atomic energy, we have been told that we now live in the age of atomic power. Actually, such extravagant claims have often been made for atomic energy that it is difficult for the layman to assess correctly just where we stand in relation to the "atomic age." He can easily rule out the extreme predictions that are obviously written for purposes of sensationalism, but an orderly view of the possibilities and problems simply cannot be obtained without recourse to a few important technical facts.

With what we have learned about the basic principles of atomic energy, however, we are now in a position to evaluate the extent to which we have entered the age of atomic power, just how much atomic power is available, just how it will be produced, and finally how much it will cost. This last point concerning economics is essential, for, regardless of the unlimited nature of atomic energy, it still must compete in the market place if it is to become an important part of our industrial life. The fundamental principles of fission and the chain reaction determine quite directly these practical questions; it is necessary only to add to the basic facts some information about the practical methods of using the chain reaction for motive power or the generation of electricity to assess properly the probable place of atomic power in our present and future life.

The Energy Available from Fission

In considering the practical use of matter itself as a power source, through the mechanism of fission, the first question we must settle is the obvious one: how much atomic power is available? There would be little point in getting excited about this new power source should tremendous quantities of uranium be required. When fission was discovered in 1939, little was known about the amount of available uranium. If uranium should be rather scarce, there would be even less reason for optimism.

Here, however, we can give the answer almost immediately: there can be an enormous amount of atomic power, even if uranium should be scarce. We can give this answer because we remember that the energies involved in nuclear changes are millions of times greater than those involved in such chemical changes as the burning of oil or coal. These nuclear changes, in which matter itself is converted into energy in an amount given by Einstein's equation, result in production of unbelievably large amounts of energy from uranium. As we have already seen, when uranium undergoes fission only about 0.1 percent of the matter disappears in the process. Yet, in accordance with Einstein's equation, involving the large number representing the velocity of light squared, the energy that appears is not at all small.

We have considered in Chapter 3 how calculations based on Einstein's equation lead us to expect a large energy release in fission. Thus, if *all* the atoms in 1 pound of U^{235} should undergo fission, the 200 million electron volts released by each fissioning uranium atom, added for all the atoms in the pound, would produce an amount of energy that is difficult to comprehend. The results are made even more impressive by the realization that the 1 pound of U^{235} would make a cube only slightly larger than an inch on edge. This small cube of U^{235} loses only one-thousandth of its mass, or about one-sixtieth of an ounce, when all its atoms undergo fission. Yet this tiny loss in mass results in an amount of energy of 11 million kilowatt hours in electrical units. This electricity is about $500,000 worth at the rate we usually pay for electric power in our homes. In still other units, as we have seen, the amount of energy obtained from this 1 pound of U^{235} is the same as would result from the burning of 200,000 gallons of gasoline or from the burning of 1,500 tons of coal. It is no wonder that the imagination is fired by the prospect of such amounts of energy from the destruction of only a sixtieth of an ounce of matter.

Yet, difficult as they are to comprehend, these energy equivalents are not some vague promise of the future. They are inevitable consequences of the mass disappearance in fission, and they correctly give the energy output of all chain reactions that are in operation at the present time. Thus there is an exceedingly large amount of atomic energy available in small bits of fuel. The compactness of atomic fuel is extremely important with regard to power production in some remote regions where coal and oil are not available. In fact, as we shall see later, it is in just such regions that the promise of electrical power produced from the atom seems most real in the near future.

And we need not worry about the total amount of uranium actually available. Uranium had not been much sought after before the discovery of fission, for it was a material of relatively low value in that period. Since then, however, intensive search has uncovered more and more uranium, and at the present time the known recoverable reserves of uranium (plus thorium, which, as we shall see, is also a possible fuel) are equivalent to some ten times the known recoverable deposits of oil, gas, and coal. So we have little to worry about for a long, long time concerning the availability of atomic fuels. Furthermore, should we ever run out of atomic-fission fuels, we could at that remote date probably turn to the abundant hydrogen and use it in the fusion reaction. It will be more appropriate, however, to consider this possibility in the last chapter, for it is still a thing of the distant future.

The First Step in Power Production—Heat

It is clear, then, that even small bits of uranium can produce much energy, which in theory at least can then be turned into motive power or electrical energy. Obviously, we must now look into the manner in which the energy, in an amount fixed by Einstein's equation, is turned into much more prosaic forms, say the energy of electricity traveling along transmission lines or of high-pressure steam in the turbine of a submarine.

The energy represented by Einstein's equation appears in the act of fission as energy of motion of the fragments of the uranium atom, the rapidly moving *fission fragments.* If these fission fragments move through solid material, their energy is soon dissipated as heat; if many atoms are undergoing fission in the material, it is rapidly raised to a high temperature. At the present time, all practical methods of getting energy from fission involve the intermediary stage of a hot substance as an energy-transfer agent; in other words, the fission fragments are always allowed to turn their energy of motion into heat. It is a fundamental fact of power generation that electrical energy cannot be obtained from heat with high efficiency; in fact, two-thirds or more of the energy is usually lost in the process. It is a tempting thought that perhaps the energy of motion of the fission fragments could be turned *directly* into electrical energy without going through the stage of heating a material. In principle this direct conversion of atomic energy into electricity is possible but the difficulties are so great that it is not being considered seriously at the present time.

In the accompanying diagram (Fig. 16) we show, again "in principle," how this direct conversion of fission energy into electrical energy could be accomplished. The uranium undergoing fission is present as a very thin film of material so that the fission fragments emerge from it before their energy of motion is converted into heat. The fragments are electrically charged positively because they lose some of their surrounding electrons during the violent fission. Thus the metal plates on which the fragments land soon become positively charged, while the thin foil from which the fragments leave becomes negatively charged. The plates are connected to the terminals of a large condenser outside the reactor. The electric charge on the plates is thus conducted to and stored in the condenser, which is thus a source of electricity at very high voltage, actually many millions of volts. Here the energy of the fission fragments would appear directly as electrical energy, and not merely one-third but *all* the energy. If the electricity were used to do external work, thus removing electric charge from the condenser, it would be replaced by the charges carried by the moving fission fragments. A great advantage of this type of reactor is that it would produce no heat.

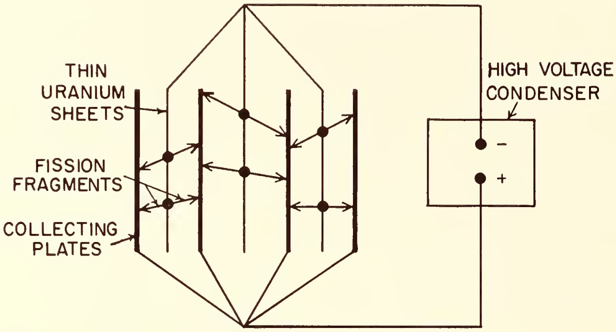


Fig. 16. A method by which, in principle, energy of fission could be turned directly into electrical energy. Great difficulties, explained in the text, make this method essentially impossible.

The difficulty with this simple idea is that the central foil must be extremely thin to allow the fission fragments to escape, so thin that it would not contain enough uranium to make the chain reaction operate unless thousands and thousands of such foils were used simultaneously. Excellent electrical insulation would also be necessary to keep the charge from leaking off the condenser under an electrical potential difference of many millions of volts. In addition, the space between foils and plates would have to be a vacuum to ensure freedom of motion of the fission fragments. These difficulties are sufficiently great that no serious attempt is being made to utilize direct conversion of fission to electrical energy. All the work that has been done so far on power production starts with the prosaic method of a hot material for energy transfer.

But in the form of heat, inefficient as it is, a very large amount of atomic energy has already been produced in the United States, mainly at the large chain-reacting piles at Hanford, Washington. These nuclear reactors operate at power levels that are still classified, but certainly above 100,000 kilowatts for each reactor. The heat is not used to generate electricity, however. The purpose of these large nuclear reactors is to make plutonium from U^{238}, the plutonium being destined for use at the present time in bombs. The intense heat production in the reactors is merely a by-product at the present time; the heat is removed by high-velocity, high-pressure water, which flows past the uranium rods of the reactor, carrying away the heat. The hundreds of thousands of kilowatts of power thus carried out of the reactors by the cooling water perform no useful function. In terms of power, the net result of the whole process is that the temperature of the Columbia river below Hanford is a fraction of a degree higher than the temperature of the river above the Hanford plant. Here we have heat generation on a large scale but no conversion to useful forms of power.

The Need for High Temperatures in Reactors

But if we are to use this heat as a means of motive power or to generate electricity, how are we to proceed? From one standpoint the problem is simple, for the methods of turning the energy represented by heat into other types of energy is one that has been thoroughly investigated, over many years of effort. Whether water has been heated and converted into steam by the energy of fission or by the simple burning of coal, its use in turning an electrical generator is the same. However, much more is involved in the generation of atomic power than the simple addition of a Hanford-type nuclear reactor to a conventional coal-burning electrical generating station. The major reason is that the hot water of a Hanford reactor is not a very efficient medium for driving an electric-power plant. What is needed is some coolant material that can be raised to a much higher temperature, a temperature sufficiently great that high-temperature, high-pressure steam can be generated; the steam drives a turbine, which in turn can drive an electrical generator, as sketched in Fig. 17.

The material that removes the heat from the nuclear reactor, that is, the *coolant,* can be raised to a higher temperature by increasing the power level of the reactor. The increase in power level is simplicity itself, for it is accomplished merely by regulation of the control rod. However, as the power level is increased the natural limits of various materials in withstanding high temperature soon furnishes a severe restriction. For example, the uranium metal itself, if heated too severely, changes its shape. The resulting distortion of the uranium-metal *fuel rods* can cause serious mechanical difficulties in the functioning of the reactor.

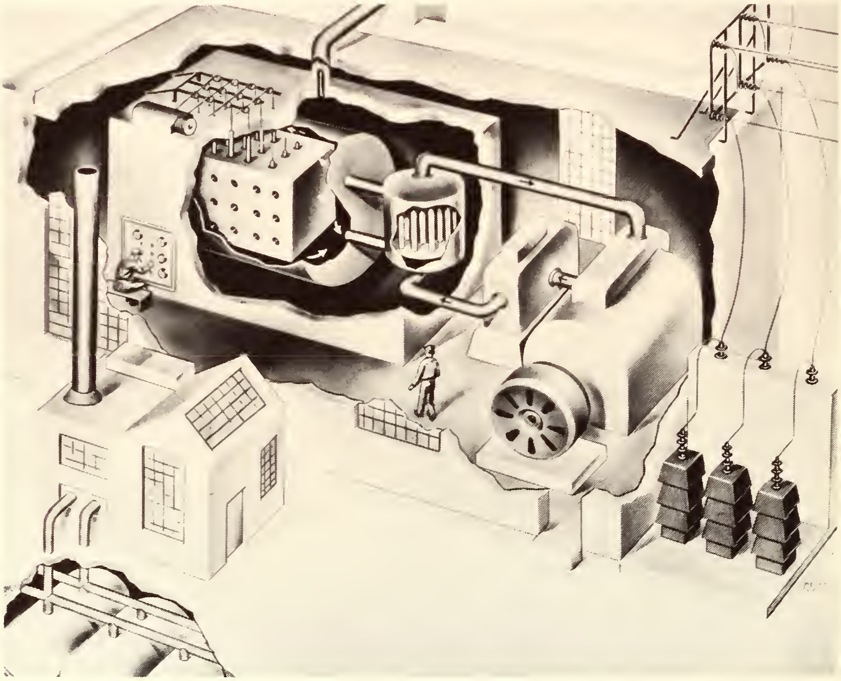


Fig. 17. The principle of the method that is used with reactors for the production of electric power. The energy of fission appears as heat, which is carried by a coolant material, here shown as a gas, to a boiler (center of picture) where steam is produced, which in turn drives an electric generator (right).

Furthermore, the uranium rods must be covered with a protective coating of some type so that the fission fragments themselves do not escape into the cooling stream. Because of the intense radioactivity of the fission fragments, it is not safe to allow them in the coolant because they would then circulate throughout the plant and constitute a definite hazard to personnel. The matter of coating the uranium rods with some material that can withstand intense temperatures is one of the greatest difficulties in the atomic-energy industry at the present time. But much has been done on these developments and high temperatures can now be reached in recent reactors. Various coolants other than water can also be used but, as we shall learn, not in a reactor using natural uranium because, while they may have desirable heat-transfer properties, they may also absorb too many neutrons. However, when enriched uranium, containing a higher proportion of U^{235} than in natural uranium, is used in a reactor, these other coolants become possible.

The Problem of Shields

Assuming then that some cooling material can be made sufficiently hot to be efficient for generating electricity, let us see what other problems are new in the generation of power from the atom. Compared with conventional methods, the additional factors that must be taken into account arise from the other two inevitable products of the chain reaction—neutrons and radiation. Both neutrons and the other radiations, primarily gamma rays, are intensely dangerous when emitted in the intensities typical of high-power reactors. Because of the hazards involved, it would be completely impossible to operate a reactor without a protective *shield* surrounding it. The heavy shields involved limit greatly the diversification of reactor types that will be available to man in the atomic age.

Soon after Hiroshima and Nagasaki we were all told that our cars would be powered with atomic energy, that tiny atomic engines would heat houses, and furthermore that these things would require essentially no fuel. But these tempting vistas must be sharply curtailed when we take into account the realities of shielding. Perhaps the best way to illustrate the necessity of shielding and its importance is to consider the feasibility of small atomic engines. It is true that such an engine could be built, which would fit under the hood of a car and would certainly require less than a spoonful of fuel per year. It would have to be made of U^{235} so that the size of the reactor would be sufficiently small; it could be cooled by some gas, which could then drive a small gas turbine. But when we consider the intensity of radiation and neutrons emitted by this chain reaction we see vividly the important effect of shielding on the practicability of the entire scheme.

The gamma radiations emitted by our automobile engine would be very similar to those from *radium,* which, used correctly, can successfully treat disease, and in large amounts can kill. To establish a standard of comparison, we refer to the fact that the radium in use in all the hospitals in the world and in other applications at the present time, if combined, would amount to about 5 pounds only. We can see in a dramatic way how potent our automobile engine would be, with regard to gamma radiation, when we calculate the amount of radiation it would emit when operating at, say, 100 horsepower. The radiation intensity is the same as would be emitted by 1 ton of radium—1 ton compared to the entire world's radium supply of a mere 5 pounds. Of course the radiation emitted by typical large nuclear reactors is much greater than 1 ton of radium would emit, but in these cases the radiations are stopped by the heavy shielding walls that have been built for them. We could design such a shield for our atomic automobiles as well, in order to protect the driver, passengers, and pedestrians, but when we do we find that it would weigh 50 tons! This then is the reason why small atomic engines of the automobile type are extremely impractical in the foreseeable future. Large shields are no disadvantage at all for stationary power plants and even for ocean-going vessels, but they raise great difficulties for airplanes, for example, and practically insuperable barriers for atomic automobiles.

The fact that the shields that must be placed around nuclear reactors are inevitably so large and heavy deserves somewhat further comment. One might well say, "We know that you scientists say that shields are heavy now but we are sure you will think of some way to stop the radiations with a thin, light-weight shield." Unfortunately, the inevitability of massive shields is one of those few things about which we can be absolutely definite. The reason is that the physical laws concerning the behavior of radiations, and the interactions in matter that can stop them, are extremely well understood at the present time. The chance is essentially nil that any new process for stopping radiation will come to light in the future. Furthermore, the phenomena that do stop radiation all involve weight, for the stopping of the radiation is simply a matter of getting sufficiently many heavy nuclei in the path of the radiations.

The detailed manner in which radiations lose energy and are finally stopped is a matter of great complexity and the design of the optimum shield for a given type of radiation is therefore very difficult. Extensive researches, both experimental and theoretical, are now going on in order to design the best types of shields, but these researches will enable us to decrease the weight of shields by only small percentages. This is not to say that these small percentages are unimportant, because for certain applications, such as an atomic engine for an airplane, even small decreases in shield weight may be of supreme importance. But these advances in shield design do not give the kind of improvement that would be necessary to make an atomic automobile possible.

The effect of shield weight is thus a very important consideration in the future possibilities of atomic power and it may be summarized quite accurately and simply thus: The atomic automobile is almost impossible because it would require a 50-ton shield; the stationary power plant or the large ocean-going liner will not suffer appreciably because of the large shields; the shield weight is a problem for the submarine but the success of the "Nautilus" shows that it is not insuperable; the airplane has as one of its most difficult problems shield weight, but success seems like enough to justify the present tremendous efforts; and lastly, the atomic locomotive, while not impossible, seems at least in the distant future.

The Uranium-Graphite Reactor as a Power Source

As our interest is primarily in the peacetime applications of fission, we can turn to the principal such application, the production of electricity, where shield weight is not a serious worry.

The type of nuclear reactor that we have so far considered is the one made with natural uranium, consisting of 139 atoms of U^{238} to each atom of U^{235}, suitably arranged in graphite as a moderator. If we were to use this type of reactor as a power source, it would probably resemble the large reactors at Hanford, in which the heat is removed by rapidly moving water. However, at the present time there is no serious consideration given to this method of producing atomic power from a *natural-uranium reactor,* that is, using the hot water from a Hanford-type reactor to operate an electrical generator. The reason is simply that hot water is not a very efficient source of electrical energy. It is a simple and well-known fact of power generation that the *efficiency* of the process, the fraction of the heat energy that is actually converted to electricity, depends very sensitively on the temperature of the material that is used to carry the heat energy.

It is because of this effect of temperature on the efficiency that steam generating plants through the years have gone to higher and higher temperatures, involving higher and higher steam pressure. However, if we should try to get the water in a Hanford-type reactor to higher and higher temperature, which could be done without the water boiling by letting the pressure increase sufficiently, we soon run into difficulty. The difficulty arises because it would be necessary to have very strong steel pipes to carry the water through the reactor to withstand the high pressure. On the other hand, unfortunately, the presence of these steel pipes would result in absorption of so many neutrons that the chain reaction could not take place. Returning to our former technical terminology, we would say that the nuetron absorption would then be so high that the reproduction factor would drop below unity.

The fact is that ordinary uranium and graphite, even with no extraneous neutron-absorbing material, have a reproduction constant only 5 percent above unity. This low reproduction factor means that a reactor even without neutron absorbers must be rather large, of the order of 15 feet across, to chain react at all. A smaller reactor has greater neutron leakage and if this leakage were larger than 5 percent for the case that we have discussed ($k = 1.05$) no chain reaction would result. If we desire to remove large amounts of heat energy from the reactor it is necessary to have large amounts of coolant, say water, in the reactor at a given instant, together with the strong pipes necessary to carry the coolant. In the Hanford reactor the amount of water must be kept small and further it is carried in aluminum pipes because steel would absorb too many neutrons. These limitations with regard to the amount and kinds of structural materials and coolants means that the amount of heat that can be removed, and the temperature of the coolant that is reached, are severely limited in a reactor made of natural uranium and graphite.

However, it is possible to extract useful power from a natural uranium–graphite reactor even though the efficiency is very low. Of course there is a great incentive to realize the attainment of power from a natural uranium–graphite reactor because it is the only type of reactor that does not involve the use of any separated isotopes. Separated isotopes represent a vast expenditure of capital and are available only in an atomic-energy program that has already continued a number of years.

The first reactor of the unseparated-isotope variety that gave any useful power was the reactor called BEPO at Harwell, England. Most of the reactors, called "piles" at the time they were built, were named in such a way that the initial letters formed a catchy word, in this case the "British Experimental Pile" with the last letter arbitrarily added for euphony. BEPO is a reactor containing natural uranium and graphite, which is cooled by blowing air through channels surrounding the uranium rods. The hot air emerging from the reactor, which would normally be sent up a tall chimney and dispersed into the atmosphere, is circulated first past a *heat exchanger* where it heats other air, it itself being too radioactive to be used further. After giving up its heat to the *secondary air,* the *primary air* from the reactor, now somewhat cooler, passes up a chimney and out to the atmosphere. The secondary air, warmed by the radioactive air from the reactor, is then sent throughout several buildings. The process, while somewhat crude, and not a matter of generation of electricity, does heat several large buildings and saves the establishment some 500 tons of coal per year. A similar arrangement is now in effect at Hanford where the hot water from several of the reactors is caused to warm other water, for the same reasons used in the British reactor, mainly to avoid radioactivity. The *secondary water* at Hanford, though not very hot, is still warm enough to be used to heat several buildings. These uses of heat from the reactor are certainly by-products, the main purpose of the Hanford reactor being production of plutonium, and of the British reactor, the production of neutrons for research purposes. Actually the amount of heat energy obtained in these cases is much less than the electrical power used in operating the reactor, so if this method were used primarily for heat production, it would be pointless.

In spite of the inherently low efficiency of production of energy in a natural uranium–graphite reactor, there is one atomic power station now operating that utilizes this type of reactor, namely, the Calder Hall plant in Cumberland, in the northern part of England. Here two reactors are now operating, cooled by a gas, *carbon dioxide,* CO_2, used because its absorption of neutrons is extremely small. The carbon dioxide gas is pumped through the reactors very rapidly, with the reactor running at a sufficiently high power level that the temperature of the gas is high enough to make steam as it passes through a heat exchanger outside the reactor. This steam operates a conventional turbine, which in turn drives an electrical generator.

The fundamental reason why the British are building reactors of a type that would be considered much too inefficient in this country, is the urgent need of the British for atomic power. We shall soon discuss some of the simple economics of atomic power, but it is obvious that a country whose coal supplies are rapidly dwindling can "afford," that is, "must" use, atomic power even in the inefficient form represented by a natural uranium–graphite reactor. A Calder Hall reactor operates at sufficiently high temperature that the heat produced amounts to about 180,000 kilowatts. However, of this power only 40,000 kilowatts appears as electricity to be sent out over the transmission lines, in spite of the large size of the reactor. The ratio of 40,000 to 180,000 is 22 percent, which is thus the over-all *efficiency* of the plant. The efficiency has a very close connection, as we have seen, with the temperature of the coolant, being inevitably fixed by it.

Reactors with Separated Isotopes

When separated isotopes of uranium or of hydrogen are available, the possibilities for reactor types increase enormously. *Heavy water,* containing heavy hydrogen (H^2) instead of ordinary hydrogen (H^1), is not much different from the usual light water in atomic behavior, but its neutron absorption is only about one-thousandth that of light water. Thus, if heavy water is used as the moderator in a reactor instead of graphite, the neutron absorption is much less, the excess reactivity is greater, and the possibility of including a variety of coolants and structural materials then opens. In other words, the heavy water absorbs so few neutrons that it is possible to lose some in other materials.

When enriched uranium is used instead of natural uranium, even greater amounts of coolants and structural materials may be included and the size of the reactor can be much smaller. This follows simply because removal of some of the U^{238} atoms saves many neutrons, which would otherwise be absorbed in U^{238}, so that they can cause fission in U^{235} and promote the reaction. In fact, even the arrangement of uranium in lumps may then be dispensed with and the so-called *homogeneous reactor* becomes possible. Here the uranium is held in solution in the fluid circulated through the reactor, which fluid also removes the heat. The moderator itself may be omitted, in which case the chain reaction can still be sustained provided the fuel is very enriched, even though the neutrons are moderated only slightly. In such a *fast-neutron reactor* the average neutron energy is of the order of hundreds of thousands of electron volts, instead of the 0.02 electron volt for the slow or *thermal-neutron* reactor. We shall not devote more time at the moment to the various reactors that can be designed utilizing separated isotopes; later in this chapter we shall describe the more hopeful types now being constructed in the United States.

Breeders

With the great variety of types of reactors that are possible using enriched fuel it is possible to consider more complicated overall programs than the simple attainment of electrical power. One of these goals is *breeding,* which refers to the possibility of making more fissionable material in a reactor by neutron absorption than is actually consumed as fuel. An example of a reactor in which breeding might be attained is one containing Pu^{239} as fuel and in addition some U^{238}, the nonfissionable uranium isotope. Capture of a neutron in U^{238} produces U^{239}, which becomes Pu^{239} after emission of two beta particles. If the number of Pu^{239} atoms thus produced exceeds the number destroyed by fission in the chain reaction itself, then breeding is accomplished. Strictly speaking, breeding is the term applied only to the production of the same kind of atoms as are present as fuel, whereas *conversion* is appropriate for the process in which a different kind of fissionable atom from the fuel itself is produced. In addition, breeding *usually* implies a net gain of fissionable material (*breeding gain* greater than unity), while the term conversion is used even though a net loss occurs (*conversion ratio* less than unity). The usual natural uranium–graphite reactor is a converter, for it consumes U^{235} and makes Pu^{239}.

We have just described how neutrons are lost in this type of reactor by absorption in U^{238}, and from the illustrative figures we have considered it is obvious that the amount of plutonium made by this process is less than the amount of U^{235} consumed by fission, hence the conversion ratio is less than unity. However, with the availability of enriched fuel a reactor can in principle be arranged so that breeding gains or conversion ratios greater than unity actually are attained. For example, the constant η for U^{235} is 2.08 for slow neutrons as contrasted with 1.35 for natural uranium. Of the 2.08 neutrons produced in U^{235} (augmented slightly by the fast effect) one must be consumed to propagate the chain reaction and another to make an atom of fissionable material to replace that destroyed. Of the approximately 0.08 neutron remaining, some loss will result from absorption in impurities and in structural materials, but what remains represents the net gain in number of fissionable atoms per generation, because each of these remaining neutrons will produce Pu^{239} if absorbed by U^{238}. Similar considerations show that a reactor using U^{233} as fuel, for which η is 2.31, has an excellent chance to be a successful breeder. In this case the 0.31 extra neutron would be decreased slightly by unavoidable absorption in impurities and structural materials and the remainder would be available for absorption in the thorium metal surrounding the reactor. The thorium, specifically Th^{232}, becomes Th^{233} upon capturing a neutron and, after loss of two beta particles, transforms to U^{233}. The breeding principle, as exemplified for the Th^{232}–U^{233} case, is illustrated schematically in Fig. 18. Neutrons emitted during fission in the U^{233} fuel leave the central reactor section, or *lattice,* and are absorbed in the surrounding thorium "blanket," thus producing more U^{233}. Use of Pu^{239} as fuel in a slow-neutron reactor does not seem favorable for breeding or conversion, because its value of η is only barely above 2, namely 2.03. However, as η for Pu^{239} increases greatly at higher energy it is promising as a fuel for breeding in a fast reactor.

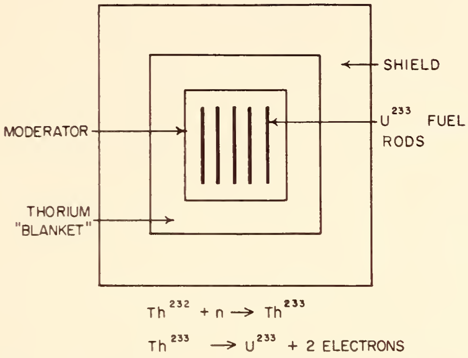

SHIELD
MODERATOR
U^{233} FUEL RODS
THORIUM "BLANKET"
$Th^{232} + n \rightarrow Th^{233}$
$Th^{233} \rightarrow U^{233}$ + 2 ELECTRONS

Fig. 18. The principle of a "breeder" in which more fissionable material is manufactured in the blanket than is consumed in the reactor lattice.

There is perhaps less emphasis on the process of breeding at the present time than there was some ten years ago, when physicists were first seriously considering the future of atomic power. At that time most of the work was being done by theoretical physicists who were attracted by the principle of breeding and its far-reaching possibilities, and treated it in a mathematical manner, neglecting many pertinent practical details. When these considerations are included, however, such as the capital cost, the compromise of a design to optimize breeding with maximum heat output, and the loss of fissionable material in chemical processing, the attractiveness of a marginal breeding project is much less.

The United States Power-Reactor Program

In order that nuclear fuels, U^{233}, U^{235}, or Pu^{239}, may be used for power, it is necessary to develop reactors in which electricity can be produced at a price about the same as that for existing power stations. The problem is obviously not a simple one, as can be judged by the magnitude of the effort in the United States, where the Atomic Energy Commission plans to spend about $300 million in five years on this problem alone. In addition to this amount of money to be spent by the AEC, further large sums will be put into power development by private industries. In the July 1956 report of the AEC to Congress it is estimated that private industry will invest $358 million in the development of atomic-power plants in the next five years.

These sums, large as they seem, cover only those designs far enough along to be suited for actual construction. Many types of reactors are being considered that are not yet at a commercial stage, but, in order to emphasize the real imminence of atomic power, it is better not to speak of things in the distant future, but to talk about those reactors that are actually building or are planned for building in the near future.

These are not vague possibilities but actual power-producing reactors that will be running in a few years, producing real electrical power, which will be put into the national power lines and used in homes and industries. It is true that in general this power will cost more than power produced by conventional methods in the United States. However, the cost of power from these reactors will be less than what is being paid for power right now in parts of the world where conventional fuels are very scarce. After we consider in broad outline these power reactors of the near future, we shall be better able to examine the cost figures, both in the United States and abroad.

The details of these reactors, for those who wish the highly technical matters, can be found in unclassified reports of the AEC; good general guides are the semiannual reports of the AEC to Congress, obtainable from the Government Printing Office, Washington, D. C. But for the ordinary citizen who does not have the time or training to dig into technicalities, it is perhaps useful to go briefly over the reactors in the construction or design stage. Such a review will be effective in showing the magnitude of the effort at the present time in the United States, and the probable course of the entry of atomic energy into our power system. There are extensive power programs in Great Britain and the USSR also, but we shall limit our discussion of reactor types to those of the United States at present. As our program is concentrated on advanced types and almost all of the important details have been released, the United States program is an apt one to illustrate all the possibilities of atomic power. In Chapter 7 we shall take up the more general international aspects of atomic power, especially with regard to its possible role as a potent example of international understanding and mutual help.

There are several types of reactors, now in the construction or advanced design stage in the United States, for the production of power at a high enough level to make them comparable with an average-sized coal-burning power station. These are still referred to as prototype power plants, and are thus regarded as experiments on a grand scale, which must be tried in order to find a design that gives the most efficient production of power. A brief survey of these reveals the wide scope of the designs under investigation.

1. *The Pressurized-Water Reactor.* The type known as a *pressurized-water reactor* is one in which water under pressure as high as 2000 pounds per square inch is used as the coolant. The reason for the high pressure is that water under pressure can be raised to a high temperature without boiling. In this case the water reaches a temperature of about 500° Fahrenheit, well above the 212° boiling point of water at ordinary pressure. The hot, high-pressure water emerging from the reactor is circulated through *heat exchangers* containing pipes in which the water produces steam at a lower pressure, such as 600 pounds per square inch. This steam in turn is used to drive electric turbo-generators, in just the same manner as is done in a coal-burning plant. The generating capacity will be 60,000 kilowatts of electrical power or more, depending on which specific design is used. Actually at present three different designs of pressurized-water reactors have been proposed for construction.

One of these designs is for a reactor now nearing completion at Shippingport, Pennsylvania. It is being built and will be operated by the Duquesne Light Company of Pittsburgh, which has assumed up to $5 million of the cost, the remainder being supplied by the Atomic Energy Commission. The AEC will sell the steam generated by the reactor to the power company at rates to be determined by the cost of fuel and other factors that enter into the economics of power production, probably 1 cent per kilowatt hour, slightly higher than conventional power. A drawing of the over-all power station is shown in Fig. 19. The Duquesne Light Company will supply the conventional generating equipment, while the reactor itself was designed by the Westinghouse Electric Corporation. The reactor will use about 100 pounds of highly enriched U^{235} as fuel, and surrounding the reactor there will be a *blanket* of natural uranium, mainly U^{238}, weighing 12 tons. The function of the blanket will be to capture neutrons in U^{238} and thus produce plutonium, the process constituting *conversion,* as we have just seen.

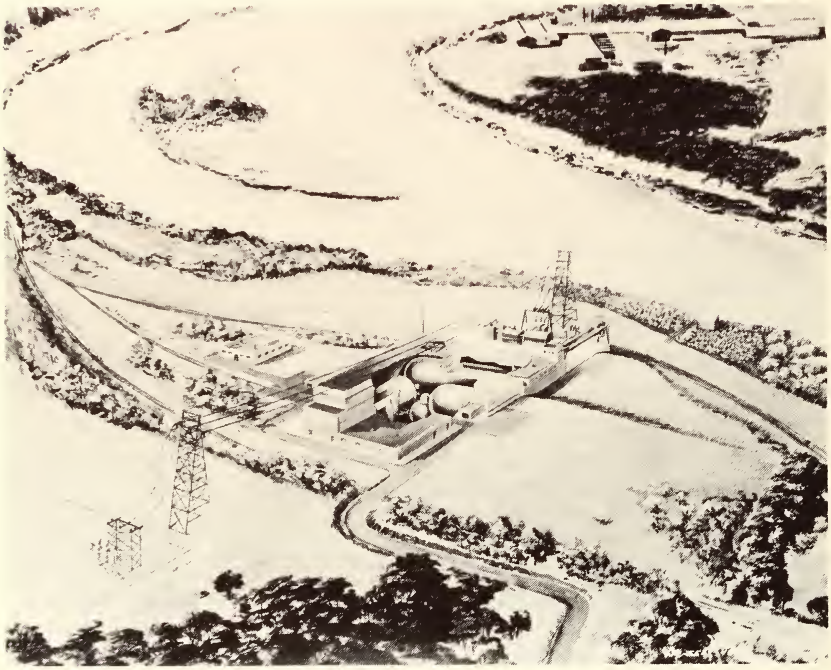


Fig. 19. An over-all view of the atomic-power plant being built at Shippingport, Pennsylvania. (Courtesy of Westinghouse Atomic Power Division.)

The plutonium can be recovered from the uranium fuel by chemical means after the uranium has been in the reactor for a matter of some days. Actually the reactor will not produce as much plutonium in the blanket as the amount of uranium consumed in the reactor, for only about four atoms of Pu^{239} are produced for each five atoms of U^{235} consumed by fission in the reactor. In this case it is said that the *conversion ratio* is 4 divided by 5, or 0.8.

Another type of pressurized-water reactor has been proposed for Western Massachusetts by the Yankee Atomic Electric Company, composed of twelve coöperating concerns, which will be aided by AEC funds, under the latter's *Power Demonstration Program.* In this program, the Commission will not charge for the fissionable material supplied for a period of 7 years. The reactor will contain about 30 tons of uranium, enriched only slightly, to 2.7 percent of U^{235}, as compared to the almost pure U^{235} of the Duquesne reactor. It will supply 134,000 kilowatts of power, more than double the 60,000 kilowatts of the Duquesne plant. The reactor will be built by Westinghouse and the entire station is scheduled for operation in 1960.

A third design of this type is that of the Consolidated Edison Company, which is being built at Indian Point, New York, by the Babcock and Wilcox Company. Consolidated Edison is paying for the reactor completely with its own money. This reactor will also use highly enriched U^{235} as fuel and will have a blanket of 10 tons of thorium, which yields U^{233} after absorption of neutrons. Thus, in its initial operation, the reactor will be a converter, but after sufficient U^{233} has been produced in the blanket to serve as fuel, operation as a true breeder would be possible, if a *breeding gain* greater than unity can be achieved. In addition to 160,000 kilowatts supplied by the reactor there will be 110,000 kilowatts obtained from the burning of fuel oil, which serves to superheat the steam, thus making possible higher efficiency in the conversion from heat to electric power.

A vital factor in the design of any reactor is the avoidance of corrosion, primarily at the point of contact of coolant and uranium fuel. The problem becomes especially difficult to combat wherever water at high temperature is involved, and necessitates the use of corrosion-resistant materials. Not only must these materials resist chemical action but their nuclei must possess the property of absorbing very few neutrons as well, so that they may be used for promoting the chain reaction and for breeding or conversion. The metal zirconium has been found to satisfy these requirements to a high degree, and has thus become one of the important, though expensive, ingredients of reactors designed for power production. The whole problem of designing fuel elements whose protective jackets can withstand high temperatures, be comparatively inert chemically, and absorb few neutrons has been a very difficult one for chemists and metallurgists. Such considerations have led to other designs which do not use water as the coolant but a liquid metal, such as sodium, or an alloy of sodium and potassium. These coolants also make it possible to operate the reactor with little slowing of the neutrons, thus making the *fast-neutron reactor* possible.

2. *The Fast-Neutron Breeder Reactor.* A reactor known as a *fast-neutron breeder* is scheduled for 1959 completion by the Detroit Edison Company, together with several other firms, with AEC financial assistance. It is being designed to have an electric capacity of about 100,000 kilowatts. A striking feature of this reactor (Fig. 20) is the small size of the chain-reacting *core* plus its surrounding blanket of natural uranium, which occupy a space only 3 feet in length and 3 feet in diameter. The fuel has a 20-percent enrichment in U^{235} and amounts to about 5000 pounds. The coolant is molten sodium metal operated at a temperature of 800°F and a pressure of 100 to 200 pounds per square inch. Steam temperature will be 730°F, which permits a higher efficiency to be realized in conversion from heat to electrical energy than is possible with the lower temperature range of the pressurized-water reactors. As its name implies, this reactor operates with fast, unmoderated neutrons and thus has greater breeding possibilities, since the value of η is greater for higher-energy neutrons. The reactor will be similar to the experimental fast-neutron reactor that has been in operation at Arco, Idaho, for about two years. Because of a minor accident at this Arco reactor, in which some of the fuel rods were melted, there has been some concern about the safety of the Detroit reactor. However, the AEC insists on extremely rigid safety tests before any high-power reactor near population centers can be put in operation. Fears in this respect seem to be superfluous, for operation of the reactor will occur only if the "Reactor Safeguard Committee" is fully satisfied that no disaster will occur.

3. *The Sodium-Graphite Reactor.* An even higher temperature than those already mentioned is being planned for a *sodium-graphite reactor,* which will be located in Nebraska and operated by the Consumers Public Power District. This reactor will generate 75,000 kilowatts of electricity, using about 50,000 pounds of uranium, which will contain 1.8 percent of U^{235}, and thus will be only

slightly enriched by comparison with natural uranium, which contains 0.7 percent U^{235}. The reactor will reach a temperature of 925°F and generate steam at a temperature of 825°F. The sodium coolant flows through holes in the fuel rods and in the surrounding graphite rods, all the rods being clad in zirconium. The graphite serves as a *moderator* for the neutrons, slowing them down to the temperature of the graphite; thus the reactor is a slow- or *thermal-neutron* reactor. The core, cylindrical in shape, has a diameter of over 17 feet and a height of 14 feet. A second core has been designed in which the fuel will be a combination of thorium and U^{235}.

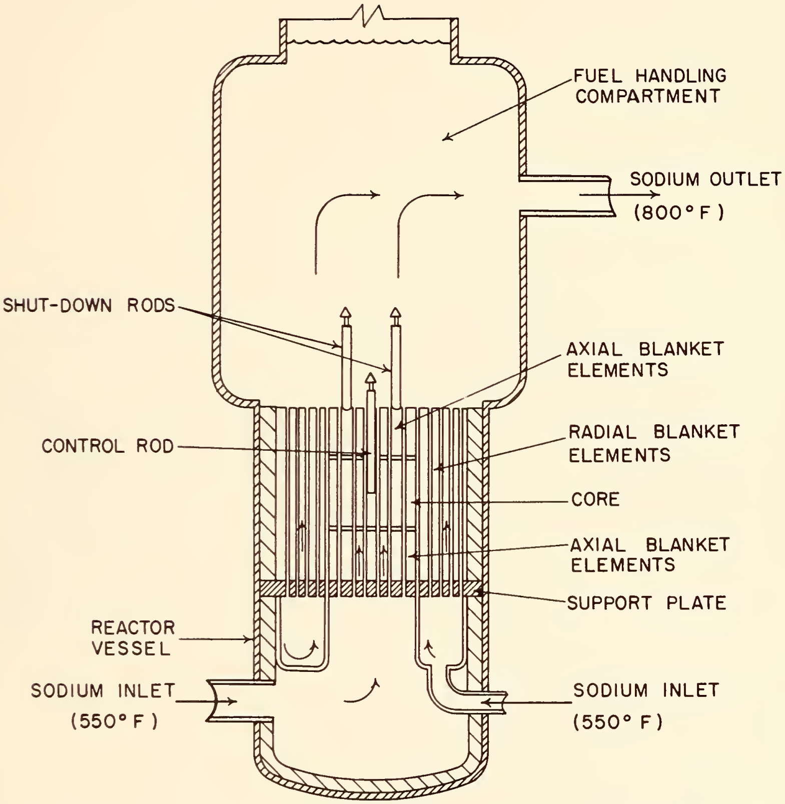


Fig. 20. The fast-neutron breeder reactor in which there is no moderator to slow the neutrons and in which the coolant is a liquid metal, sodium. (Courtesy of Detroit Edison Co.)

The latter combination has been estimated to give a higher conversion ratio, which promises to be close to unity, or one atom of fuel produced for one atom of fuel "burned." Estimates of cost of operation and maintenance for the uranium-fueled reactor have been given as 11 mills (1.1 cents) per kilowatt hour, and for the thorium reactor 9 mills (0.9 cent) per kilowatt hour, with future possibilities for a core of the latter type producing power at 6.0 to 7.0 mills per kilowatt hour. A drawing is shown in Fig. 21 of a design of a complete plant of the sodium-graphite type provided by North American Aviation, Inc., which is now building a small experimental reactor near Los Angeles to test the operational characteristics of sodium-graphite reactors.

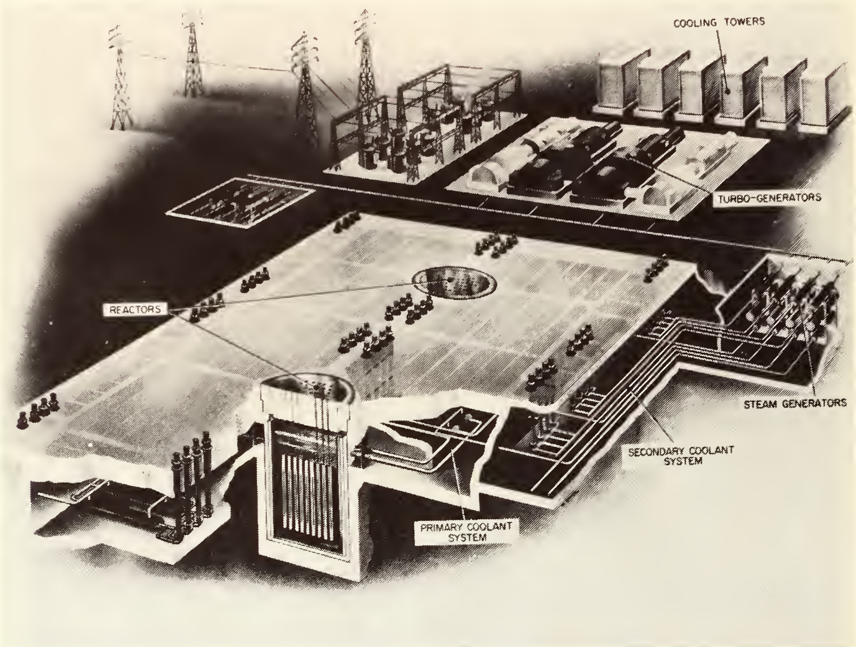


Fig. 21. A suggested power plant utilizing two sodium-graphite reactors, in which the moderator is graphite and the coolant is liquid sodium. (Courtesy of North American Aviation, Inc.)

4. *The Boiling-Water Reactor.* A reactor that differs radically from the preceding ones in the manner in which steam is generated is the *boiling-water reactor,* shown in Fig. 22. Instead of having a heat exchanger through which the coolant is circulated in order to make

steam, this reactor produces steam inside the reactor core itself, which is situated in a vessel containing both the water moderator and the fuel. The fuel will contain 1.1 percent of U^{235} and amount to nearly 150,000 pounds in a particular reactor of this type that is being planned by Commonwealth Edison and others at a location near Chicago. The reactor will be financed completely by Commonwealth Edison and is scheduled to be finished in 1960. It will operate at a temperature of 480°F and generate 180,000 kilowatts. An experimental version of this type of reactor has been in successful operation for about one year at Arco, Idaho. A great advantage of such a reactor is the simplicity of its design, which dispenses with heat exchangers and many expensive complexities of other types. The cost of construction and operation of the experi-

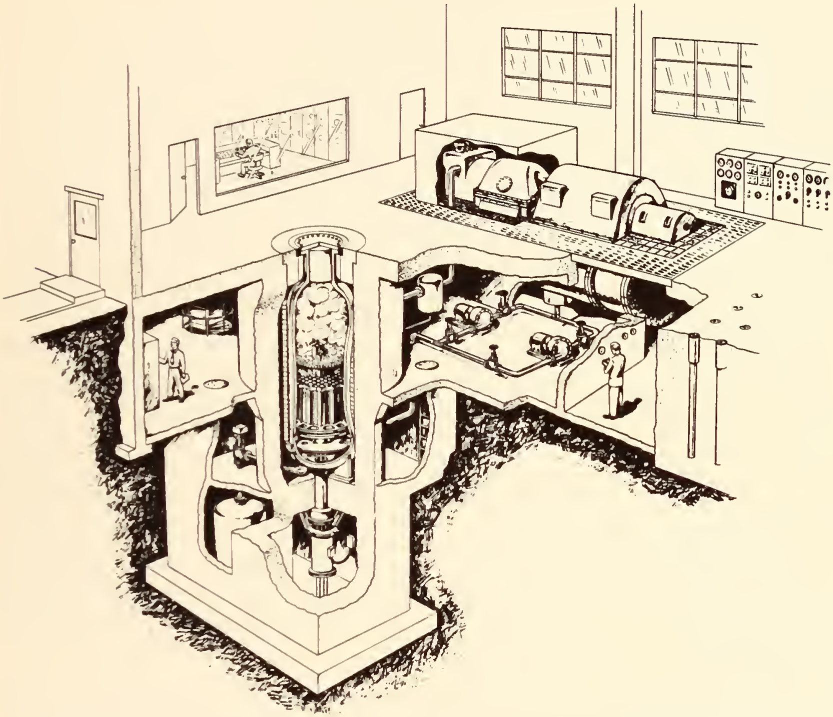


Fig. 22. The boiling-water reactor, in which steam is generated directly in the reactor itself; hence no heat exchanger is necessary as it is for the reactors in Figs. 19, 20, and 21. (Courtesy of United States Atomic Energy Commission.)

mental reactor proved to be about twice that of a coal-burning plant of comparable power, a ratio that makes it competitive with coal in many parts of the world where the latter fuel is not plentiful.

5. *The Homogeneous Reactor.* In all the foregoing reactor types the fuel elements are of solid uranium, which must be clad in some material capable of withstanding high temperatures and possessing the requisite chemical and nuclear properties for satisfactory performance. A method of avoiding the difficulties associated with the metallurgy of solid fuel elements is to use as the fuel a uranium compound that is soluble in water. The fuel can be dissolved in heavy water, which serves as a moderator for the neutrons, and absorbs very few neutrons as compared with ordinary water. Such a reactor is known as an *aqueous homogeneous reactor.* This general type has numerous advantages: it has a high degree of nuclear stability (no control rods are necessary, since the higher the temperature of the reactor the more it tends to slow down the reaction); reactor fuels can be purified continuously as the solution passes outside the reactor, thus removing undesirable fission fragments; the mechanical design is simplified by having no control rods and no need for structural materials in the reactor core itself. There are some undesirable features that go with these advantages, namely, the corrosion problems of the tank container and its associated plumbing, the high pressure, about 2,000 pounds per square inch, which is necessitated by the high temperature of the water, and the necessity of confining a large volume of highly radioactive liquid in such a way that leaks are made almost impossible. Further, the deuterium and oxygen that are produced by the decomposition of the moderator must be safely recombined.

A plant utilizing such a reactor is being planned for eastern Pennsylvania and will be owned and operated by the Pennsylvania Power and Light Company, being built entirely with private funds. It will generate 150,000 kilowatts and should be ready for operation in 1962.

Another type of homogeneous reactor now being investigated at the Brookhaven National Laboratory uses a solution of uranium fuel in molten bismuth. This design (Fig. 23) is called the *liquid-metal-fuel reactor.* The design retains all the advantages of the aqueous type and avoids some of the disadvantages, notably the decomposition of the water and the corrosion problems associated with water at high temperature and pressure. The AEC has contracted with the engineering firm of Babcock and Wilcox to concentrate on the engineering aspects of an experimental reactor of this type, while Brookhaven will carry on the research work pertaining to the reactor proper.

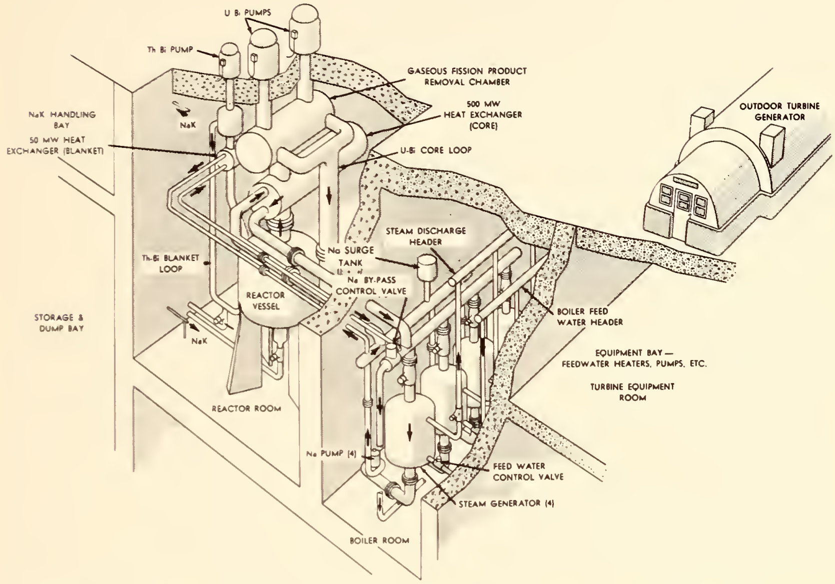


Fig. 23. The liquid-metal-fuel reactor. In this design the uranium, instead of being in the form of solid rods, is carried in solution in the liquid-metal coolant, bismuth. Another liquid metal, sodium-potassium (NaK), carries the heat to the steam generator.

The foregoing list of reactors will give only a temporarily correct picture of the nuclear-power program, as it is continually being expanded and revised. Many of the experimental and research types of reactor have not been described, as they are too varied in form and power level to permit their inclusion in such a brief summary, nor do they properly come under the head of power reactors. It is possible and even likely that some of these advanced reactor types now under consideration may turn out to be extremely promising, and that in a few years full-scale power reactors of these types may be selected for actual construction.

Even though conventional fuels are still available in great quantities in the United States, it is evident from the brief review we have just completed that there is a vigorous program for building of atomic-energy facilities in the United States. Even without atomic energy the United States generating capacity has doubled since 1945 and is now 100 million kilowatts. Present estimates are that this generating capacity will be multiplied by a factor of six by 1980, at which time one-sixth of it, that is, a capacity equal to our total present-day capacity, will be of nuclear nature. Estimates of this type of course involve many uncertainties, but progress so far has been sufficiently encouraging that, while the actual date may be wrong, there can be little doubt about the ultimate significant role to be played by atomic fuels in the power field.

The Economics of Atomic Power

Thus far we have been concerned with the principles of the chain reaction, the various types of reactor that are possible, and the practical problems that arise when large amounts of electricity are developed from fission heat with reasonable efficiency. In all this discussion we have not concerned ourselves at all with cost but have acted as if all manner of separated isotopes, as well as such materials as beryllium, sodium, potassium, and bismuth, are freely available. It is certainly time now that we confront reality and face the important question of what all of this is going to cost. Even if atomic power is possible in principle, it must also be competitive with power produced from natural fuels if it is to have any real future as a significant economic factor.

It is of course possible to make the assumption that atomic power *should* be developed regardless of cost—that it eventually will be used no matter how expensive it is. The reason for this extreme position is simply that our other fuels will presumably all be exhausted some day and we *must* then turn to atomic power. There is some justice in this argument, especially at the present time in the United States, where the known developments in power production from the atom do not supply electricity at a price cheaper than results from production by burning coal, oil, or gas. If we were to delay building large power-producing atomic reactors until they could be guaranteed to supply electricity at a price cheaper than other forms of fuel, it could very well be that such large plants would *never* be built. It could very well be that this short-sighted principle would mean that development in the field would be hopelessly retarded.

But of course the argument that cost is unimportant because of the future limited availability of other fuels is really not a neglect of the economic factors at all. As the usual fuels become scarcer, their price will rise higher and higher, until it reaches the point where atomic power will be cheaper no matter how expensive it is in absolute terms. So again we see that the cost of atomic power, even though it be only a relative cost, is of extreme importance in determining the probable course of atomic-power development. Inevitable though the development may be, as a practical matter its speed of realization in the next several decades depends very sensitively and intimately on the economics of atomic power.

We can see almost immediately that the price of electricity produced by atomic energy cannot be much less than present prices in a country such as the United States, where the "fossil fuels"—coal, oil, and gas—are readily available. The reason for this fact is that for atomically produced electricity much of the equipment would be the same as we now find in existing power plants. True, the heat source that is used for producing the superheated high-pressure steam will be quite different—an atomic reactor instead of a coal-burning boiler, for example—but all the succeeding stages in the power plant would be identical. Thus the steam turbine that operates the actual electrical generator would be the same in either case, as would the generator itself. The high-tension transmission lines that carry the current throughout the countryside and the transformers that are used to lower the voltage to that appropriate for use in homes and factories would likewise be identical. All of these items, which would not differ for atomic and conventional electrical production, represent in their totality a large fraction of the price that appears on the customer's bill. As a result, this large part of the price could not be reduced, only that small part representing the cost of the fuel itself and the boiler being capable of reduction by the realization of atomically produced electrical power.

In the United States this fraction of the price of electricity that goes for fuel is very small, about 5 to 20 percent, the exact percentage depending on type of plant and location. Thus the reduction in the actual price of electricity by the substitution of atomic energy for fossil fuels would *at best* be the same, 5 to 20 percent. The great advantage of power from fission at present comes not in a country such as the United States, where fuel is easily available and plentiful, but in countries where fuel must be transported a long distance in order to be used to generate power. For in such a case, instead of the shipment of thousands of tons of coal to the plant, it is a matter of carrying mere pounds of uranium.

As a result of the extremely small fuel requirement, it is possible to build a plant with practically complete freedom as far as location is concerned. This freedom of location is reflected in the fact that extremely long transmission lines for the electricity produced need not be provided. So in addition to the saving on the fuel cost in certain localities, where fuel is not readily available, the saving in transmission-line expense could be of great importance. The savings in shipment of fuel and in ease of location relative to transmission lines provide a great advantage for atomic electrical power but only for those countries in which these items have already made the cost of electricity high.

An important aspect of these economic facts is that the very countries that stand to reap the greatest gains from atomic power are precisely the ones that, because of lack of industrialization, are not in a position to use the electrical power at once. This is the cogent reason for the great benefits to be gained from international coöperation in the development of atomic power. In this way the nations best able to advance with atomic power may realize its benefits more quickly through the help of the highly developed countries. Later we shall describe the recent, extremely hopeful developments in the international atomic effort, which seems destined certainly to help mankind in a strict physical sense and may even augment man's political well-being.

Pricing a Power Reactor

We have just seen that electrical power produced from atomic energy cannot be much *cheaper* than that produced from conventional sources in a country rich in fossil fuels, such as the United States. However, we were careful not to imply the impossibility of the other conclusion—that atomic energy might be more expensive. This other conclusion might be correct simply because the cost and maintenance of a nuclear reactor might be extremely great compared to a coal-fired boiler, for example. So the problem of the possible extra expense of atomic power relative to conventional methods at the present time really revolves around the matter of building a nuclear reactor that comes somewhere near competing in price with a conventional boiler.

While uranium fuel is not negligible in price, it already is cheap enough that the fuel cost is no primary worry; of course it will get even cheaper as refinement methods are improved—and at the very time that coal, oil, and gas are becoming more expensive because of dwindling supplies. Thus the primary concern is not one of fuel cost but of the price of the reactor, not only its initial cost but its capability of operating for a long time without expensive repairs. This matter of the lifetime of a reactor is of supreme importance to atomic-power economics, but it is largely an unknown factor. It is a matter about which very little is known in spite of its relevance to the whole business of atomic energy because the life history of something as complicated as a reactor is difficult to predict; in a very real sense only actual operating experience can give the answer to this problem—and little operating experience is available.

The reason for the extreme importance of the reactor lifetime is the difficulty of making repairs, for, after running for some time, a nuclear reactor is extremely radioactive. In fact, it is impossible to approach the central section, or core, of a reactor to make repairs, even after it has stopped operating, because of the high intensity of radiation emitted by the fission fragments. For days or weeks after a reactor has been turned off, the radiation intensity is so great inside it that repairs there are never attempted. As a result, the reactor really must be designed so that failures necessitating repairs have a vanishingly small probability of occurring.

The types of reactor that we have described briefly all involve rather unusual materials and extremely unorthodox methods of manufacture. The very encouraging fact is, however, that, in spite of the novel features of reactors, the construction costs for the ones that are now planned are low enough that the price of such a reactor is actually comparable to those of present boilers using fossil fuels. The figures presented at the Geneva Atoms-for-Peace Meeting in 1955 led to the conclusion that an atomic-power plant would cost about twice the price of a coal-fired boiler at the present time. In absolute figures, the price of an atomic-power plant would be approximately $300 per kilowatt capacity; thus a large plant of the types we have described, say 200,000 kilowatts, would cost $60 million or more. When one realizes the inevitable improvements that will certainly occur in a field yet so young it is not at all inconceivable that the price for the two types of boiler—atomic and fossil-fueled—will become about the same within the next few decades.

The Price of Atomic Electricity

Attempting to estimate the actual price of electricity as so many cents per kilowatt hour to the ultimate consumer for an atomic-power plant is extremely complicated because it involves such matters as the possibility of selling the plutonium made in a reactor to the government. It depends sensitively on the rate at which the plant becomes obsolete and to a lesser extent on the price of uranium fuel, which is itself a complicated matter because of the close control still exerted by the government over fissionable materials.

However, in spite of the uncertainty and absence of operating experience, there is reasonable agreement among various atomic economists as to the manner in which the various parts of the expense should be calculated, and even with regard to the actual results themselves. The agreement is sufficiently good that rather firm figures are now being quoted with confidence for what atomically produced electricity will cost in the plants that are now being designed. However, in examining the costs we must be very careful what conditions are assumed in the accounting. Thus, the first large-scale producing plant in the United States, the one at Shippingport, Pennsylvania, will produce electricity at about 5.2 cents per kilowatt hour. This figure looked at in an uncritical way would be extremely discouraging, for the most modern coal-burning plants produce electricity at about 0.6 cent per kilowatt hour, that is, 6 mills per kilowatt hour. The deceptive nature of the figure of 5.2 cents or 52 mills per kilowatt hour for Shippingport is that it represents a large amount of development work that went into the reactor. Thus when the first charge of uranium is used in the reactor and a second loading is made the price will drop sharply, and succeeding loadings will produce electricity at still lower rates, eventually approaching 14 mills per kilowatt hour.

At the other extreme we have the General Electric reactor at West Milton, New York, where arrangements were made to sell to nearby communities for the unbelievably low figure of 2 mills per kilowatt hour. This figure is completely unrealistic and is arrived at by some involved bookkeeping contingent upon the fact that the plant is actually operated for the government so that experience may be gained with that particular reactor. The reactor is cooled with liquid metal and is actually the land-based prototype of the reactor that was developed for propulsion of the atomic submarine "Sea Wolf," and that now is in use in the submarine.

The most realistic figures are not for these extremes but for a reactor that is not selling plutonium to the government nor being used by the government to learn about submarine propulsion. It is better to pick a reactor that is a stationary power plant, whose sole aim is to produce power in a reliable way and at as low a figure as is consistent with the limitations of present design. The reactors being built by large power companies such as the ones we have described will produce electricity eventually in the range of about 7 to 9 mills per kilowatt hour. None of these reactors has yet accomplished this production, we must remind ourselves, but the cost estimates are not optimistic propaganda, but reasonably conservative, careful predictions. Thus even at this early stage of atomic-power production we see that the reactors can almost compete with coal, even in the United States where coal is plentiful and situated so that it can be mined with high efficiency.

Atomic Economics Outside the United States

The figures we have just considered illustrate how in the United States, in spite of its rich fossil-fuel resources and the incipient nature of atomic power, the new fuel can almost compete economically with conventional fuels. Considering the inevitable improvements in this rapidly developing field in the next few decades, we realize that atomic power certainly will compete, even in the United States, after this time has elapsed. Furthermore, it can compete with conventional fuels right now in countries where fuel is not so easily available as in the United States.

To take an example reasonably close to home, let us consider the situation in São Paulo, an important industrial city in Brazil. São Paulo is a large modern city with a population of about three million but most of its power comes from generators fueled with diesel oil, oil that must be imported into Brazil. As a result of this inefficient procedure, electric power costs about 15 mills per kilowatt hour to produce in São Paulo. Here is a case where atomic power even at its present stage of development can successfully compete with oil; because of this fact the Brazilians are greatly interested in building an atomic-power plant, not as an experiment but simply because it will give them cheaper power than they now have available. It is almost certain that the atomic-power plant for São Paulo will be built by an American company, although the details are not available completely as yet.

In many other countries similar to Brazil, where fuel is not easily available, atomic plants even in their present state of development could certainly compete successfully with coal and oil. A case more or less intermediate between the United States and Brazil is that of England. Here the atomic-power plants at Calder Hall, which have recently started operation, produce power that is relatively expensive because of the conservative nature of these natural uranium–graphite reactors. However, because coal is gradually becoming more scarce in England, and the price correspondingly higher, these rather old-fashioned reactors are just about at the stage where they can compete with coal-fired boilers in England. Such reactors could not compete at all with coal in the United States, but in England, because coal production is becoming more and more difficult and expensive, the Calder Hall reactors from the very beginning produce electricity at almost exactly the same cost as does coal.

There are difficulties in arriving at firm figures in cases like Calder Hall for they involve a high degree of government participation and the use to which the plutonium produced in the reactor is put is an important factor in the economics of the power production. The atomic economists argue at length about just how the various items of cost are to be considered, but after long discussions the final results do not differ too greatly from individual to individual. Thus in England the price of electricity produced at Calder Hall will be about one penny, that is 1.2 cents or 12 mills, per kilowatt hour. This price is rather greater than that estimated in the United States for reactors now under construction, but in England the figure of 1.2 cents per kilowatt hour suffices to compete with coal. It is worth noting that if a reactor like that at Calder Hall were built in the United States the price of power from it would be higher than that quoted for England because of higher construction costs.

It is the great potential application to countries that are poor in power sources that makes atomic energy of such tremendous appeal to these countries. It is no wonder that their scientists and engineers were so eager to acquire knowledge at the Geneva Atoms-for-Peace Conference in 1955 and to gain help from the large countries that have uranium available. The great advantage of reactors that use separated isotopes, that is, heavy water or U^{235}, over those using only natural materials means that such separated isotopes are of tremendous value in starting an atomic-energy program in a country that has none at the present time. Breeder reactors could be built in those countries but, if it were first necessary to make the separated isotopes, their programs would be held back by years and the price of the program would be multiplied manyfold. It is for this reason that help from the large countries that have separated isotopes can do so much to get the smaller countries into the atomic-energy business.

Of course, it involves much more than provision of separated isotopes, for the building and operation of nuclear reactors is a highly complex activity, and these countries usually do not have the engineers and scientists available for that necessary development. Thus it is not only a complicated problem in supplying all the necessary isotopes but in supplying the teaching and the personnel at the same time. We shall look a little more at these complicated aspects of international coöperation when we near the end of our volume.

It is difficult to estimate how rapidly atomic energy will be used in these countries where it is needed so badly. Somewhat paradoxically, we can estimate much better how rapidly atomic power will be introduced in the United States and in England where other power sources are more available. Thus the estimate presented at Geneva by the United States was that about 10 percent of the electrical power generated in the United States would be produced from atomic energy by the year 1970. In England the forecast has been made that by the year 2000 more than half of Britain's power will be atomically produced. In Russia, which like the United States is a country with rich natural resources, some billion kilowatts of atomic electricity will be available by 1960, but no forecasts have been made for the more distance future.

Because the great need in the world today is for power, as represented by electrical power capacity, there is not much serious effort, taking the world as a whole, put into estimates of the applicability of atomic energy for motive power. The engines for propelling ships, submarines, and airplanes are all of military application at the present time. These engines perhaps can be used for civilian applications but their cost is now so great that the more immediate gains to mankind, considering such practical matters as economics as well as technical details, will certainly come from stationary plants producing electricity rather than atomically driven vehicles.

When we realize all the technical difficulties in the way of production of electricity from atomic energy, we might feel that the estimates of the experts are unduly optimistic. However, in science and engineering things seem to develop even faster than the greatest optimism of the experts. Here it is good to recall the years 1944 and 1945, when atomic scientists in their few spare minutes from working on the development of the bomb would speculate on the future peacetime possibilities of atomic energy. They could foresee so many difficulties that many of them thought atomic energy would never be a practical source of power production. And those of us who were in those discussions are certainly amazed at the progress that has taken place in a mere dozen years since that time. Perhaps the progress of the next dozen years in the economic application of atomic energy will surprise the much greater number of experts who are now discussing the same things. But before trying too hard to peer into the future let us turn to the many other gains that mankind is experiencing at the present time from atomic energy, gains that come not from the heat produced in the chain reaction but from the neutrons and the radiation. These gains are not publicized so much as power, but they may ultimately prove to be a far greater boon to mankind than kilowatts.

CHAPTER 5

NEUTRONS FROM REACTORS

> *Thus it is proper to the role of the scientist that he not merely find new truth and communicate it to his fellows, but that he try to bring the most honest and intelligible account of new knowledge to all who will try to learn.*
>
> —J. R. OPPENHEIMER, *The Open Mind*
> (SIMON AND SCHUSTER, NEW YORK, 1955)

We have described in some detail the manner in which one of the products of the chain reaction, the heat energy, is being used for the production of electrical power at an ever-increasing pace. We now turn to a consideration of another of the products of the chain reaction, the neutrons, and their many profitable applications to basic science, engineering, and medicine.

Without question, the most widespread function of the great numbers of neutrons found in reactors is the making of radioisotopes. The tremendous variety and applicability of the radioisotopes produced by neutrons is such that we devote Chapter 6 completely to explaining their properties and examples of their accomplishments. As a matter of fact, when used to make radioisotopes the neutrons are not of great interest in themselves, for actually the radioisotopes would be as useful had they been produced in other ways, as, for example, in a cyclotron. It is the radioisotopes themselves and their applications to far-ranging fields that are of primary concern, not the precise mode of their production. In the present chapter, however, we are considering neutrons not as a means to an end, such as the making of radioisotopes, but for their own intrinsic interest. Neutrons used in a direct and immediate way are primarily applied to what is called *basic research.* It is well for us to spend some time on this use of neutrons, not only because of the inherent interest of the neutron experiments themselves, but because it gives us a chance to investigate the nature of basic research through an examination of one of its branches, nuclear physics.

The Use of Neutrons in Basic Research

Basic research in nuclear physics deals with the underlying truths concerning the structure of matter, with the laws that determine how the fundamental particles of matter interact with each other, and with the way in which these particles build up nuclei, atoms, and molecules. Basic research has no end in view other than the investigation of the structure of matter itself. Because the end and goal of basic research is not the practical application of the truths discovered, it is sometimes jokingly defined as "useless research." But aside from its humor, this definition has its value, for it emphasizes that in doing basic research scientists are not motivated by the possible ultimate social effect of their work. Their driving force is one of curiosity, not a desire for practical applicability. Of course, it has been true without exception that research, even of the most basic type, inevitably turns out to have valuable practical consequences. And of course scientists know that this is true. Nevertheless, it is *not* their motivation.

Probably another description of basic research is better, one that does not involve the motivation of the work, but rather is concerned with the generality or universality of the laws of nature that are discovered. The wider the applicability of a discovered principle to the understanding of the structure and behavior of matter, the more basic is its nature. And although it is usually true that the more basic the nature of a truth, the further it is from practical utilization, nevertheless this relation is really not an inherent quality of the definition of basic research.

The reason why neutrons from reactors lend themselves so naturally to basic research is that they interact readily with the basic constituents of matter, and by so interacting give us direct information on the way in which matter is built up of fundamental particles. Neutrons interact strongly with nuclei, for example, partly because they are important constituents of nuclei themselves.

Because of the fundamental and far-reaching nature of the information gained about matter by neutron effects, it is somewhat difficult to describe the actual phenomena discovered through the use of neutrons and their significance. The difficulty arises because the properties of the most fundamental bits of matter are often markedly different from those of large-scale everyday objects, and hence require some scientific sophistication in their analysis. However, the properties that are learned have such a great inherent interest that an effort to understand them, in spite of some difficulty with theoretical concepts, is well worth the effort. In explaining the fundamental facts we shall point out now and then that, even though the driving force in the investigation is the mastery of the fundamental laws of nature, practical applications of the laws discovered often follow very rapidly.

Whether rapidly or not, however, the great practical utility seems to follow inevitably. The story about Faraday, the British physicist, though often told, is worth repeating once more in this connection. A woman was watching some of Faraday's experiments in which he had discovered the basic principles of electromagnetism, which led to the development of the entire electrical power industry later on. Somewhat unimpressed by the simple experiments, the lady asked Faraday, "But of what use is it?" to which he answered, "Madam, of what use is a baby?"

Although it is a bit unfortunate that basic research must often receive financial support on the argument of the inevitability of practical utilization, we should not, in protest, go to the other extreme of feeling that practical possibilities, when associated with basic research, somehow make it less valuable or less noble. It is best that we realize that certain scientists, completely uninterested in practicality, pursue basic knowledge for its own sake, and that others use the results thus obtained to promote the well-being of man on a physical level.

Neutrons—Fast and Slow

Since the discovery of neutrons in 1932, their use for basic research has become so extensive that a whole field of physics has thereby been developed—*neutron physics.* The great value of the neutron is as a tool for investigating matter. The primary reason for the wide applicability of neutrons in studying the basic properties of matter is that they can interact with nuclei over an extremely wide range of neutron energies. The important interactions vary from those of extremely slow neutrons, which actually move much more slowly than the atoms of matter themselves, to those of neutrons that are so fast that nuclei become partially "transparent" to them. This enormous spread of velocities over which neutrons are of value in research is a direct result of the simple fact that the neutron has no electric charge.

Because the neutron has no electric charge, it can approach and enter nuclei even when it is moving very slowly. This behavior would be impossible for a particle bearing an electric charge, such as a proton, for the positively charged proton is repelled by the positive charge of the nucleus. As a result, a proton can enter a nucleus only when it is moving with high velocity, that is, with energy of the order of a million electron volts. An electron, of negative charge, would of course be attracted by the nucleus, but as the electron reacts very weakly with nuclear particles, it is not useful for studying nuclear interactions. A neutron, even though it is moving with extremely low speed, finds no hindrance in approaching a nucleus. Because the properties of all particles become very complex, and in some respects unpredictable, as they move more slowly, the possible interactions of neutrons with nuclei become very rich indeed.

In order to demonstrate the vast field of neutron interactions, we show schematically in Fig. 24 the extensive energy range over which neutrons can be used to study matter. The energy scale is a bit peculiar, as it must be to encompass the necessary energies—it is a scale on which equal intervals correspond to multiplying the neutron energy by a factor of ten. It is what we call a *logarithmic* energy scale, and it enables us to plot on a chart of reasonable size the great range of neutron energies. The lowest energy shown is 10^{-4} electron volt, that is, 0.0001 electron volt, "one" in the fourth place after the decimal point, and the highest energy shown is 10^{8}, "one" followed by eight zeros (100,000,000). It is no surprise then that so many of the innermost details of nuclear and atomic structure are revealed by this very wide *spectrum* of available neutron energies. Neutrons throughout this entire range, wide as it is, are used to study atomic and nuclear structure by means of a great variety of phenomena.

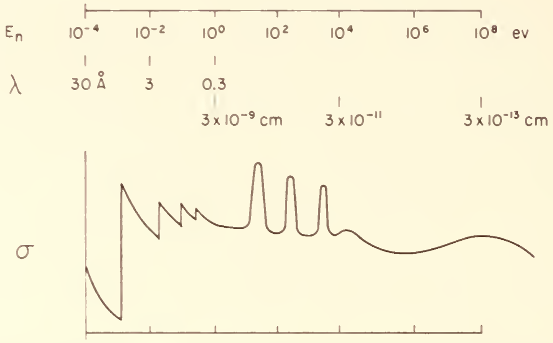


Fig. 24. The wide range in energy of neutrons present in a reactor is shown here, on a logarithmic energy scale. The wavelength λ ("lamda") of the neutrons is also shown, as is their interaction with matters expressed as the cross section, σ ("sigma").

One of the properties of neutrons, and in fact of all particles of matter, that is very difficult to visualize, but is now definitely established, is that they begin to act more like waves than particles as they move more slowly. Thus the neutron always has associated with it a particular *wavelength.* When the neutron energy, or velocity, is very high its wavelength is so small that in all ordinary ways it acts like a particle. However, as its energy decreases, the wavelength of the neutron, which can then crudely be thought of as the "size" of the neutron, becomes very large. For longer and longer wavelengths the neutron acts more and more like a wave, and the properties of very slow neutrons as they move through matter are strongly reminiscent of the properties of light waves rather than those of solid particles.

In order to illustrate the wavelength appropriate for neutrons of various energies we also plot in Fig. 24 the wavelengths, λ, corresponding to the energy scale. By ordinary standards all of the wavelengths shown are extremely small, even the largest wavelength in Fig. 24, that is, the wavelength of the lowest-energy neutron, being only 3×10^{-7} cm (about one ten-millionth of an inch).

However, relative to the distance between atoms, or the size of nuclei, this wavelength is very large. It is about a million times the size of the nucleus, and about ten to one hundred times the distance between atoms in matter. Part of the wavelength scale of Fig. 24 is expressed in Angstrom units (A), equal to 10^{-8} cm, because this unit of distance is about equal to the distance between atoms in solid material. On an atomic scale, the longest wavelength shown is sufficiently great, being thirty times atomic separations, that neutrons of this wavelength bend just the way light waves do in passing through matter and they can actually be reflected from a smooth surface just as light is reflected from a mirror. As the energy of the neutron is increased, its wavelength gets less and less, in other words, the neutron size decreases, and as the size varies, the manner in which the neutron interacts with matter varies in a complex manner, which we now consider.

Neutron Cross Sections

The manifold variations of the neutron interaction with matter requires a definite quantitative method of specifying and describing the interactions. The method is shown schematically in Fig. 24, which, in addition to neutron energy and wavelength, gives the probability that the neutron will interact with a nucleus. No particular nucleus is chosen for the purpose; rather an average behavior is selected, typical of many nuclei. This probability of interaction with the nucleus is always called the *cross section,* which we can think of with sufficient accuracy as the cross-sectional area of a nucleus as seen by the approaching neutrons. The larger the nucleus, obviously the larger the chance of the neutron's hitting it.

As the cross section is represented as an area, it could be expressed in square inches, square centimeters, or any other unit of area. Whatever the units used, however, or the language in which the accompanying text is written, the symbol for the cross section is always the Greek letter "sigma," σ. Actually, because of the minute size of nuclei the cross-section unit always used is 10^{-24} square centimeter, that is, a decimal point followed by 23 zeros and a one! This unit is called the "barn," a term originated early in the days of atomic energy to express the fact that, to a neutron, a nucleus was "big as a barn." The term has spread throughout the world and much to our surprise, at the Geneva Atoms-for-Peace Conference in 1955, the Soviet cross sections were presented in "barns," using the equivalent Russian characters, but pronounced like any Iowa barn, albeit with a rolling "r."

Obviously, the actual size of the nucleus does not change with the neutron energy; nevertheless, in a manner most difficult to visualize, the nucleus *acts* as if its size changes for neutrons of different speeds. A slightly more accurate way to describe this variation is to say that the size of the neutron varies with energy and as a result the chance of its hitting a nucleus follows a similar variation. Along with this variation of the neutron size with energy, which is smooth, we must take into account the complication that the internal structure of the nucleus is such that only for specific energies does the neutron enter into combination with the other nuclear particles, this affinity causing the abrupt changes in the cross section shown in Fig. 24.

The line in the diagram, representing the cross section of a typical nucleus, reveals that at high energy the chance of interacting with matter varies rather slowly with energy. However, at intermediate energies, the cross section is seen to rise and fall rapidly, resulting in typical peaks in the curve, called *resonances.* These peaks occur when the neutron energy is exactly right to excite a particular frequency in the nucleus. The absorption is large for that neutron energy, or wavelength, in just the way that the volume of a radio set is high when it is tuned to the correct frequency, or wavelength, of a particular broadcasting station.

As we consider neutrons of lower energy than the resonance region we enter a region where the interaction probability suddenly drops, rises slowly, drops again, rises, and so on, producing a "sawtooth" curve. The last abrupt drop carries the cross section to a very low value, and the material becomes almost "transparent" to neutrons of the corresponding energy. The abrupt drops are a result of the fact that the neutron wavelength becomes so great that it is larger than the various distances between atoms in the target material and the atoms then become much less effective in the scattering of the neutron. The final large drop occurs when the neutron wavelength exceeds the largest atomic spacing. At even lower energies, the cross section curve rises again, and continues to rise indefinitely as the neutrons move more and more slowly. This behavior results simply because such low-energy neutrons are moving so slowly that the vibrating atoms of the material itself are moving faster than the neutrons. As a result they hit the neutrons and knock them out of the material. Obviously the more slowly the neutron moves the longer it is in the material and the higher the interaction probability. Thus the curve rises continuously with decreasing neutron energy at very low energy, as shown in the figure.

Figure 24 is drawn for a typical simple material, but if it should happen to be a magnetic one, such as iron, the curve would become more complicated. The reason is that the neutron, while it has no charge, does exert a weak magnetic field, in other words, is a small magnet. Because the neutron is a small magnet it is affected by magnetic fields such as exist in iron, and the cross section then depends in a complicated way on the state of magnetization. In this way, that is, by observing the magnetic part of the cross section, the neutron can be used to study not only the ordinary atomic configuration but the magnetic structure of material as well.

The Reactor as a Source of Neutrons

When the ways in which neutrons can interact with matter vary so much with neutron energy and from element to element, it may be somewhat surprising that the vast range of neutron energy present in the reactor can be sorted out in order to obtain interpretable results. A visit to a modern research reactor with its wide assortment of experimental apparatus shows in a very impressive way that the sorting out of specific neutron energies, the primary function of the apparatus, is a formidable task. As a substitute for an actual visit to a research reactor we present in Fig. 25 a picture of one section of the large graphite-moderated reactor at Brookhaven, which does give some idea of the instrumental complexity. The wall of the reactor is at the left and some of the *beam holes* are shown; when not in use, they are closed with large plugs. The scientists are working with an apparatus in which a neutron beam is reflected from the surface of a liquid.

The way in which neutrons are distributed throughout a research reactor shows that some degree of sorting of neutron energy can be done by selecting the best working spot in the reactor for the desired energy. The schematic diagram of Fig. 26 illustrates the main internal features of the Brookhaven reactor in a simplified form. The central part of the reactor, in which the chain reaction takes place, is usually called the *lattice* or *reactor core,* as we have already learned. It is in this core that the neutrons of highest energy, those emitted in fission, are found in high intensity, and it is here within the core itself that experiments must be done that require the full intensity of these very fast neutrons. An example of this type of experiment, which we shall consider shortly, is one in which atoms are *displaced* inside materials, or knocked out of their normal positions, by the fast neutrons, with resultant surprising changes in physical properties of the material.

In the usual type of research reactor, such as the one of Fig. 25, *all* neutron energies are found in their highest intensities inside the reactor core. Hence, if it is necessary to use the largest possible number of neutrons in an experiment, it must be done inside the

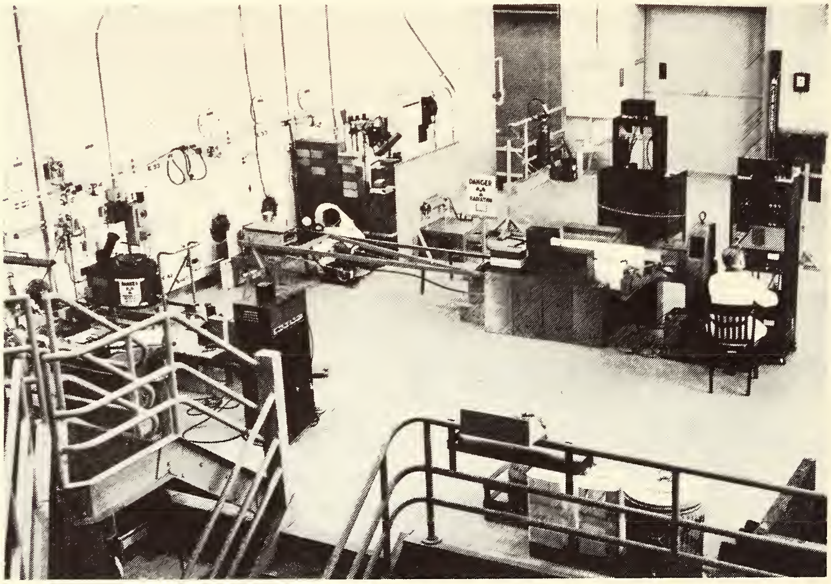


Fig. 25. A view of one section of the Brookhaven National Laboratory graphite research reactor, showing the many beam holes with their experimental equipment.

core even though the presence of undesired neutrons usually complicates the results. The neutrons inside the core may be used for radiations by inserting samples of material into the core itself, a process that sometimes involves rather elaborate handling devices. However, the difficulty of working inside the core is so great that the advantage of high intensity must usually be foregone and the experiments be performed, if possible, away from the reactor core, by means of beam holes.

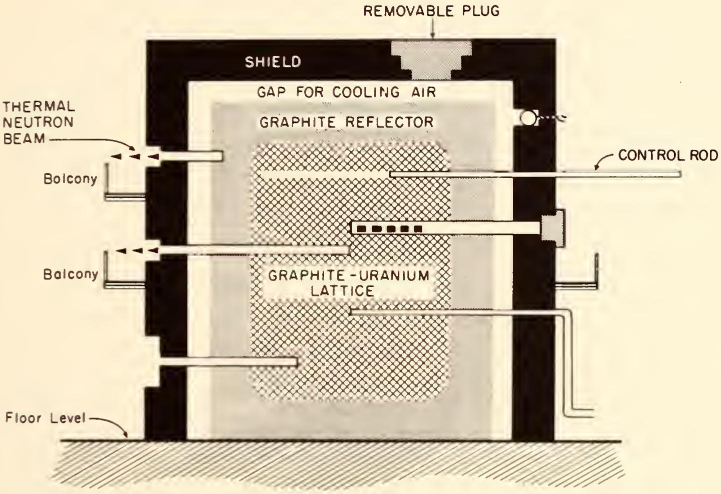


Fig. 26. A schematic diagram of the Brookhaven research reactor, illustrating the various ways in which samples can be irradiated and neutron beams obtained from the reactor.

It is possible to get the neutrons out of the reactor so that work can be done with them outside the reactor shield, where working conditions are much more flexible even though the intensities are considerably lower. The method of getting the neutrons out of the reactor is to make a long hole into the core itself, as shown in Fig. 26. From this *beam hole* there flows a mixture of all the neutron energies present in the reactor, as well as intense gamma and beta radiations. Although the intensity in such a beam is less than it is inside the center of the reactor, the favorable location outside the shield means that various elaborate pieces of equipment can then be used to separate out neutrons of desired velocities to be used in research. From the diagram we can see that it is possible to make beam holes in slightly different locations in the reactor, such as the *reflector,* where there are few fast neutrons but still a large number of thermal neutrons. Thus by picking a particular type of hole some selection of neutron energies becomes possible, but for accurate experiments it is usually necessary to sort the neutrons with greater precision after they have emerged from the reactor.

Effects of Fast Neutrons on Matter

In order to illustrate the remarkable variety of investigations that can be made with neutrons, we shall now describe a few outstanding examples of the use of reactor neutrons in basic research, beginning with the highest-energy neutrons and moving to the extremely low-energy, or "cold," neutrons. These examples all have to do with basic research, being investigations into the fundamental laws and forces underlying the structure of all matter. In almost every case, the main end of the experiments is simply to learn about the general rules governing the behavior of neutrons, protons, nuclei, atoms, and molecules. But, as is so often true, the information gained can be so quickly put to practical use that it is difficult to decide whether the study of the structure of matter or the practical application is the main motivation. Regardless of motivation, however, these examples illustrate the way in which the intense neutron sources now available, undreamed of two decades ago, are revealing how neutrons and protons form nuclei and how atoms interact with one another in a great variety of types of ordinary matter.

As fast neutrons move through matter they collide with atoms and knock them out of their positions in the ordered, or *crystalline,* arrangement characteristic of almost all solid material. Because there is a very direct relation between such *displaced atoms,* those out of their usual position, and the basic properties of solids, such as hardness and ability to transmit heat and electricity, marked changes in these properties are produced by the neutron bombardment. In order to induce these changes it is necessary to displace an appreciable number of atoms in the usual crystalline substance, hence it is essential to use the most energetic neutrons and they must obviously be present in large numbers. As a result the only practical way to produce these *radiation effects* is to place samples in the reactor core, preferably very close to one of the pieces of uranium fuel. The experimental difficulties become very great, however, for it is usually necessary to prevent the displaced atoms from returning to their places in the ordered, or crystalline, arrangement.

If the sample of material under investigation is heated, the atoms move faster and they more easily find their way back into the ordered arrangement. Hence to preserve the effect of neutron radiation it is usually necessary to keep the sample at a very low temperature during and after the neutron radiation, a very difficult task when the sample is inside the reactor core, where tremendous heat energy is being developed constantly. It is thus necessary to devise equipment in which the sample can be vigorously cooled, for example, by liquid air continuously flowing through the reactor, in spite of the intense heat produced throughout the sample by the reactor radiations. These experimental difficulties have been overcome, and the efforts have been well repaid by the importance of the results thus obtained. An example of the interesting results obtained by this radiation transformation is *radiation hardening.* It has been shown that a typical metal becomes harder during the neutron radiation and that the hardening is very similar to the well-known *work hardening* produced by mechanical deformation of the metal. Work hardening results from any process in which the metal is violently treated, as by hitting it with a heavy hammer. A rather surprising but important result is that the effect on increasing hardness of a metal seems to be a result of displacement of atoms, whether these are single atoms knocked out of position by neutrons, or the much larger sections of the material that are displaced as a whole when the material is work hardened.

The effects of radiations, such as the hardening of a metal, can often be removed if the metal is heated to a high temperature, a process that allows the displaced atoms to slip back into place. This latter change of the physical properties of a metal, the softening by heating, is the process that is known as annealing. It is obvious that the practical application of such basic studies in the nature of hardness of metals will certainly have marked practical effects. The results thus obtained are directly applicable in leading to a better understanding of the industrial processes that go into the making of myriad types of metals. These processes, developed over many years, are in many respects arts rather than science for the actual mechanisms involved are not fully understood. Thus if neutron radiation can aid in the analysis of the basic phenomena, logical steps to produce desired types of metals can be more quickly devised.

The Fast Chopper

In our brief survey of the great variety of neutron cross sections, we have already noted that neutrons of intermediate energies have interactions with nuclei that vary rapidly, and in a complicated manner, with neutron energy. The sharp peaks in the cross-section curve shown in Fig. 24 occur when the neutron wavelength has the exact value to be "in tune" with the nucleus. For these exact wavelengths the nuclear absorption, or cross section, is extremely high, in a manner closely analogous to the tuning of a radio receiving set. In order to study these peaks of absorption, or *resonances,* as they are called, it is obviously necessary to use neutrons of carefully controlled wavelength or energy.

Because of the necessity of obtaining neutrons of controlled energy to study the sharp resonances, it is out of the question to attempt to study these resonances using the neutrons inside the reactor itself. They therefore must be obtained in beams emerging from the reactor so that space is available for the elaborate equipment that selects neutrons of precise energies. Although the neutrons in a beam coming from the reactor represent a very broad spread in energy, it is possible, by means of precise velocity selectors, to sort out the individual energies and thus study the effects of neutrons under very carefully controlled energy conditions.

A very important method of obtaining neutrons of particular energies is based on the simple principle of measuring the velocity of the neutrons in terms of the time it takes them to cover a given distance. The timing is made possible by the use of a so-called *"fast chopper,"* which is a mechanical shutter that stops the neutron beam except for very short times during which it allows the neutrons to pass through it. In this way short *bursts* of neutrons, lasting only about one-millionth of a second, are produced.

The mechanism of the fast chopper in use at Brookhaven Laboratory is shown in Fig. 27. It is a rapidly rotating disk containing slits through which neutrons are able to pass when the disk is oriented with the slits in line with the neutron beam. As the disk must rotate very rapidly, it is mounted in a vacuum chamber to eliminate the air friction that would otherwise make its rotation extremely difficult. The chopper rotates at about 10,000 revolutions per minute and it is because of this extremely high speed that as the slits pass through the beam the neutrons proceed through the chopper for a time lasting only about one-millionth of a second.

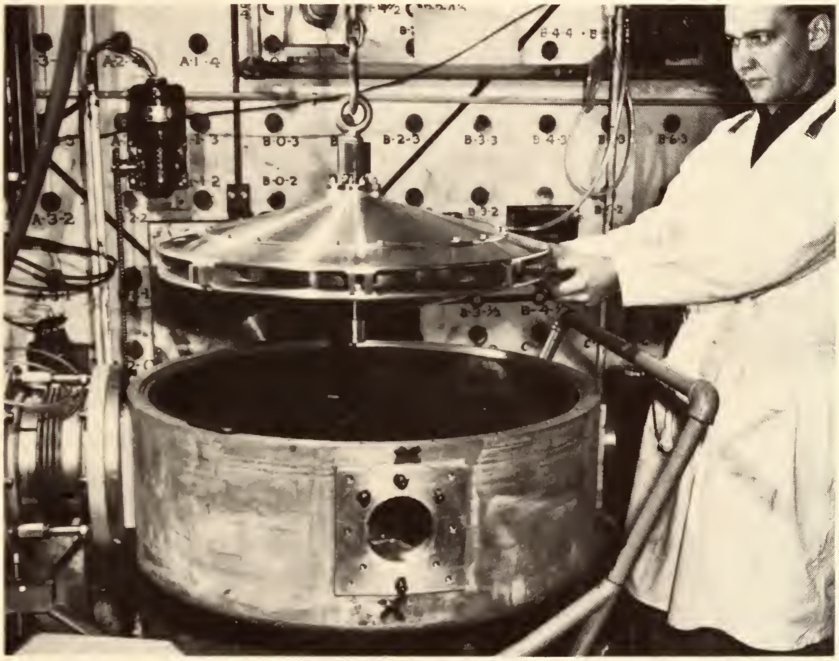


Fig. 27. The mechanical velocity selector in use at the Brookhaven reactor, or, as it is commonly called, the "fast chopper." The rotor spins at 10,000 revolutions per minute and thus creates short bursts of neutrons, whose velocities are then measured electronically.

As the burst of neutrons produced by the chopper moves toward the neutron *detector,* or *counter,* about 100 feet away, the fast neutrons get ahead of the slower ones. The time of arrival at the detector is thus a measure of the speed or the energy of the neutrons. Elaborate electronic timing circuits are usually used so that neutrons of as many as 1000 different energy groups can all be recorded during the same running period. If the neutron beam were allowed to pass the 100 feet from the chopper to the detector through air, many of the neutrons would be scattered by air molecules and so lost from the experiment. To eliminate this loss of neutrons by air scattering the beam is passed through a plastic balloon filled with helium. The scattering cross section of helium is so low that essentially none of the neutrons are lost when they are passed through it.

Neutron Resonances

The interaction of a material with neutrons of different velocities is measured by placing a small sample of the material in the neutron beam near the chopper and observing how neutrons of certain velocities are removed from the beam more readily than those of other velocities. Neutrons removed to a great extent at a particular energy reveal the fact that a resonance for the cross section is located at that energy. The resonance structure of U^{235}, shown in Fig. 28, is a good illustration of the complexity of these points of strong absorption or, as they are called, *energy levels* of the nucleus.

Investigations of resonances or energy levels in nuclei by means of the fast chopper is a very good illustration of the relation between basic research, that is, knowledge of the fundamental facts of the structure of matter, and the practical applications of that knowledge. The basic structure of the nucleus, or the interaction law of neutrons and protons, is still one of the unsolved problems of modern physics. In spite of the great amount of data that we now have concerning the properties of the nucleus, the basic reasons for its structure are still only vaguely understood. At the present time, the information learned from neutron resonances about the various energy levels—their size, the distance between them, and the variation in their characteristics from nucleus to nucleus—constitutes fundamental information used for constructing theories of nuclear structure. Thus the information gained by study of resonances is immediately available for the development of theories about the basic nuclear structure, a matter of the purest theoretical interest, with little thought on the part of the theoreticians of practical applications.

In spite of the direct bearing of resonance results on basic theory, and the fact that the theoreticians using the resonance properties may be thinking only of the pure theory, the results are equally applicable to extremely practical matters. The foremost of these is the design of nuclear reactors—primarily, at the present time, the large stationary electrical generating plants. The precise nature of the resonances in such important fissionable isotopes as U^{235}, as well as the structural materials in power reactors, such as aluminum and steel, and the coolants, such as water or liquid metals, are of vital importance in the design of efficient nuclear reactors for power production. Theory is hardly sufficiently advanced that the resonance properties of these important materials can be predicted ahead of time; it is absolutely necessary that they be measured in detail. Results of these measurements are of extreme

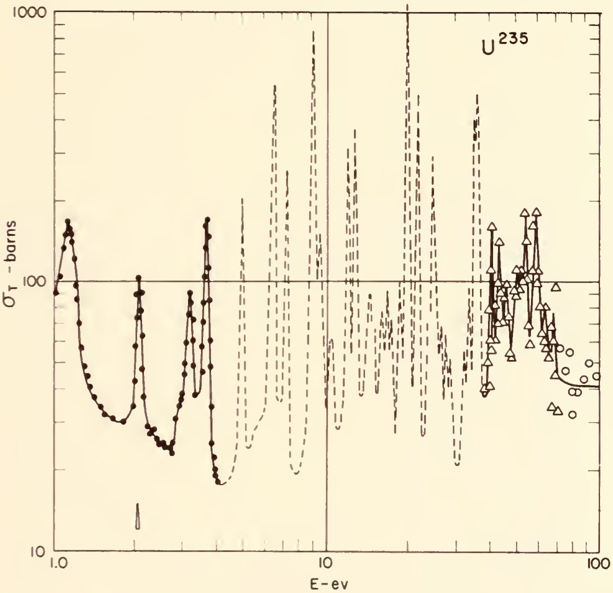


Fig. 28. The complicated cross-section curve of the important isotope U^{235}, as measured with the fast chopper shown in Fig. 27. In the central region of the curve, around 10 electron volts, the structure is so complicated that individual experimental points cannot be shown.

importance in designing reactors that will be not only economical but safe in operation.

The great importance of the precise properties of resonances in the power-reactor field arises in connection with the stability of power reactors. Thus in case the energy of the neutrons in a reactor should shift, as by a sudden rise in temperature, the neutrons may move into a strong resonance, and, depending on the properties of this resonance, the chain reaction could quickly decrease or increase in intensity. The direction of the sudden change is determined simply by the properties of the resonance, whether it produces a large amount of fission, which promotes the chain reaction, or is predominantly capture of neutrons, which hinders it. Thus if the first possibility should be true, the reaction might suddenly increase in intensity, perhaps to a dangerous degree, whereas for the other possibility, the reaction would simply slow down harmlessly. The direction of these effects is obviously of great importance in the design of power reactors, and information gained on the important fissionable isotopes is of immediate great practical use.

Neutron Diffraction—The Study of Crystal Structure

When we consider neutrons of somewhat lower energy than those used for investigation of neutron resonances, we soon get to the energy region for which the number of neutrons in the reactor is much larger than for any other energy. The atoms of all matter are in continual motion, vibrating to and fro, their energy representing the heat energy of the matter. As the neutrons decrease in energy by colliding with the moderator atoms of a reactor they finally reach an energy that is about the same as these vibrational heat energies. On the average, no further loss of energy results, and as a result there are extremely high densities of neutrons in this *thermal-energy* region in the usual reactors.

Fortunately the wavelength of neutrons corresponding to the energy of greatest intensity is just about the same as the distance between atoms in ordinary materials, about 10^{-8} centimeter, or less than one hundred-millionth of an inch. Because of this similarity in size between neutron wavelength and interatomic distance, the neutrons are extremely useful for studying the structure of ordinary materials, that is, the geometric arrangement of atoms in individual crystals of the material. For neutrons in the energy region where the wavelength is similar to the spacing between atoms the interaction or cross section changes in a rather complicated way with neutron energy, as shown at about 3A in Fig. 24. In addition to the cross section σ, in the investigation of *crystal structure* we study the direction in which neutrons are scattered from the sample being analyzed, the variation of the number of neutrons scattered with angle being extremely complicated. The graph of the variation of scattered neutron intensity exhibits sharp peaks when neutron waves from nuclei of different atoms add strongly. This addition is a typical wavelike property, which for ordinary light waves is called *diffraction.* By analogy, the neutron behavior is called *neutron diffraction.* The equipment used for diffraction work is illustrated in Fig. 29; primarily because of the necessity for extensive shielding, the equipment is rather massive.

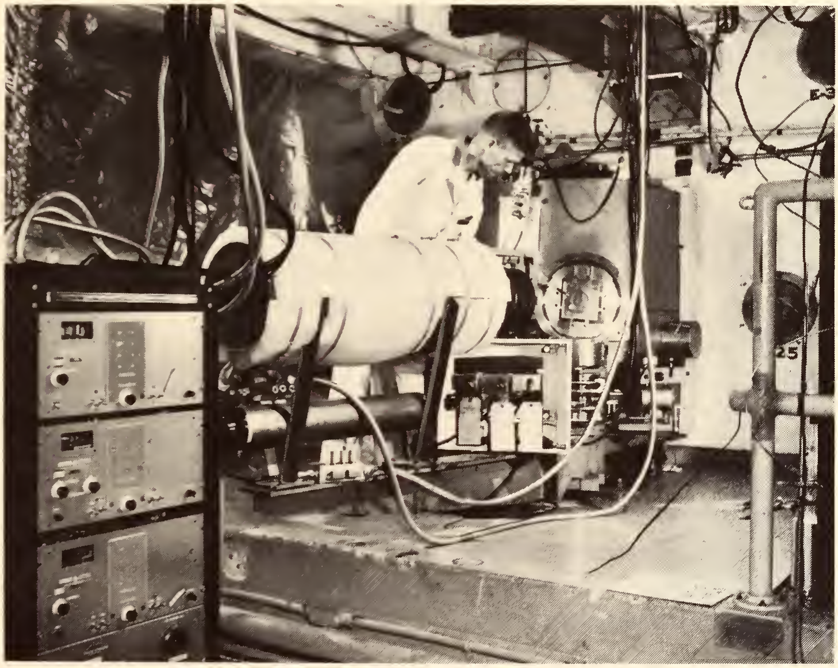


Fig. 29. The experimental apparatus that is used to study the structure of crystals with neutrons by the methods of neutron diffraction.

The complicated patterns observed for neutrons scattered from solid crystalline materials are almost exactly analogous to those obtained from the scattering of x-rays. For many years x-rays have been used in this way to study the geometric arrangements of atoms in crystals; now it is possible to use neutrons to study the structure of matter in the same way. If neutrons behaved exactly like x-rays, however, there would not be much point in using them, for the same types of studies with x-rays can determine the structure of crystals with great precision. However, neutrons fortunately do not scatter in exactly the same manner as x-rays. Because of these differences there are extremely important applications of neutron diffraction for which x-rays are unsuited.

One of the great advantages of study of structure by neutrons is in the study of crystals containing hydrogen. As hydrogen atoms, containing only one electron each, do not scatter x-rays effectively, it is very hard to study with x-rays the location of hydrogen atoms in crystals. However, neutrons are scattered by the nucleus of an atom rather than by its electrons, and the scattering depends on many things other than simply the size of the atom. Thus the neutron scattering cross section of hydrogen is rather large, in spite of the fact that its nucleus consists of only a single proton. As a result it is possible to study the positions of hydrogen atoms with the aid of neutrons, where x-rays would give practically no response to the hydrogen atoms. The crystals containing hydrogen constitute an extremely important type of materials, for they represent all the crystals related to *organic material,* that is, the materials associated with living tissue, and containing primarily hydrogen, carbon, and oxygen atoms.

Another important difference between the scattering of neutrons and x-rays is that neutrons have *magnetic dipoles,* that is, they are similar to small magnets, and are therefore scattered by the magnetic fields of materials. This result means that neutrons can be used to investigate the nature of magnetic fields far inside large solid materials, a study that could not be carried out by ordinary magnetic methods, and that is completely impossible by x-rays because they, being a wave motion, are not scattered by magnetic fields. Neutrons thus become effective tools for studying the nature of the magnetic fields inside such important things as iron, which possess intense magnetic properties. The magnetic fields of materials such as iron are extremely complicated and difficult to study by ordinary gross methods, such as measurement of the magnetic strength of a piece of iron by external means. These methods give only the average effect of the fields existing inside the material and do not reveal the extremely significant information concerning the nature of the magnetic fields around individual atoms.

Reflection of Neutrons from Mirrors

For neutrons of long wavelength, the wave properties are so dominant that it is much easier to analyze their behavior by considering them as a ray of light than as a beam of individual particles. These very slow neutrons display all the familiar characteristics that we associate with wave motion, most familiarly in connection with light, with little evidence that particles are present. When a slow-neutron beam enters a material it bends in just the way a light beam does when it leaves water and enters air, for example. Also neutrons, in spite of their extremely small wavelength in comparison with ordinary objects, can be reflected from a mirror in just the way light is reflected. The reflection takes place only when the neutron beam is grazing the surface of the mirror, however, because of the very short neutron wavelength; neutrons hitting the mirror surface at larger angles penetrate into it rather than being reflected from it.

It is necessary to select a material that does not absorb neutrons appreciably in order to have it exhibit transparency and other optical effects for slow neutrons. Although most materials show appreciable *absorption* of neutrons, some, such as carbon and beryllium, scatter neutrons predominantly, with essentially no absorption, and these materials are excellent for experiments in which very slow neutrons are to be passed through large samples. However, neutrons can be reflected externally from mirror surfaces even of highly absorbing materials because no penetration is involved. This type of optical experiment has been used to make very precise measurements of several of the most fundamental types of interaction between elementary particles, such as neutrons, protons, and electrons.

An extremely important interaction is that between the neutron and the proton, the two basic building blocks of nuclei, hence of all matter. Whereas the law of the force that is exerted between two electric charges is extremely simple and well known, the neutron-proton force is vastly more complex and far from being understood. Thus it is necessary to measure the details of the neutron-proton force as carefully as possible, for the dual purpose of using it in practical calculations of the behavior of neutrons and of furthering the theoretical understanding of the force itself. This particular interaction was studied by reflecting a very narrow beam of neutrons from a liquid surface, the liquid being one containing a mixture of hydrogen and carbon, whose proportions could be varied. It was found that the surface of a quiet liquid reflected neutrons extremely well, better, in fact, than a highly polished glass or metal mirror. By measuring the exact angle, always very small, at which the reflection could be obtained for various hydrogen-carbon proportions, the strength of the interaction between the neutron and the proton was measured to extremely high accuracy. The particular value thus determined is of great importance to theories that attempt to explain the manner in which neutrons and protons are held together in nuclei, being attracted when they are at a certain distance apart, but repelled when they approach each other too closely.

Another important fundamental interaction, which has been measured as well with neutron mirrors, is that arising from the electrical attraction between the neutron and the electron. At first sight, one would think that this interaction would be zero, for the neutron has no electric charge whatsoever, hence there should be no electric force between the neutron and the electron. However, a more detailed analysis of the situation reveals that there should be a minute force exerted between the neutron and the electron when the electron gets so close to the neutron that it can be considered to be inside the structure of the neutron itself. Here we are considering the inner structure of a particle that is considered "fundamental"—almost a contradiction in terms, for fundamental particles were long considered to have no structure. But at present we are learning, as our experiments become more advanced, that none of the basic particles is simple, structureless, and fundamental.

Although the neutron may seem to be a simple particle, having no electric charge but a small magnetic field, in more sophisticated modern theories the neutron is thought of as a complicated structure indeed. According to the present theories of nuclear forces, the neutron actually consists of a proton closely surrounded by a cloud of *mesons*. The individual mesons may be negative or positive, but the net charge of the cloud must be one unit of negative charge, to balance the proton's charge. We have already learned in Chapter 2 that the mesons fly back and forth between nuclear particles and thus serve to hold them together with great force. Should the electron get so close to the neutron that it is actually within the latter's structure, that is, between the proton and the meson cloud, then of course there would be an electric attraction between the electron and the proton. The net effect of the attraction would be extremely minute, however, because of the low probability of the electron's getting inside the very small extent of the neutron's structure. Nevertheless, this neutron-electron effect is extremely important to measure because its actual numerical value is a severe test of any theory of mesons and nuclear forces.

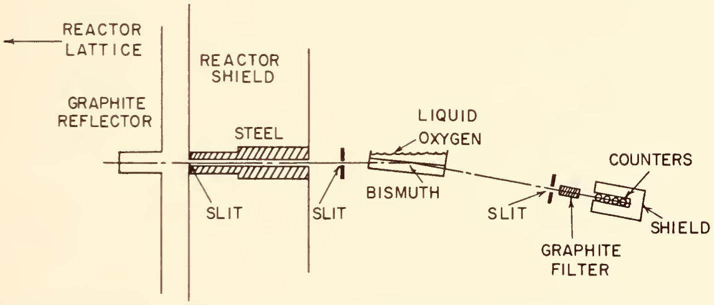


Fig. 30. The manner in which neutrons were reflected from a mirror surface between metallic bismuth and liquid oxygen. This experiment was used to measure the tiny interaction between the neutron and the electron.

This interaction was measured by reflecting neutrons from the surface of a bismuth block when the block was in contact with liquid oxygen, as shown in Fig. 30. Oxygen gas becomes a liquid if its temperature is decreased lower than 400 degrees below zero Fahrenheit, thus the bismuth mirror–oxygen combination is held in a low-temperature refrigerator, not shown in the simple diagram. The neutrons pass through the bismuth block readily, because of their long wavelength, and they are then reflected at the interface between the bismuth and the oxygen. Because of the large number of electrons in bismuth, 83 around each nucleus, and the small number in oxygen, 16, the effect of the electrons on scattering the neutrons could definitely be measured even if it were only the 1 percent of the nuclear scattering expected on the basis of meson theory. The experiment, however, showed that the scattering was much *less* than the 1 percent predicted. The real reason for the very small observed interaction between the neutron and the electron relative to that expected for the proposed structure of the neutron is thus still unexplained. It may well be that the complex structure proposed thus far is still too simplified a model of the real neutron, whose actual structure somehow results in an almost zero neutron-electron interaction.

These illustrations of the basic research work performed with neutrons show that the prime and immediate objectives of the experiments themselves is always to learn more about the fundamental forces between the "simplest" particles found in all matter —neutrons, protons, electrons, and mesons. The practical application of these discoveries is usually not a consideration at the time the experiments are being planned and painstakingly performed. It seems to follow inevitably, however, that the experiments when performed give information that will have definite practical results. In some cases the practical results follow almost immediately, as is so well exemplified by the studies of resonance structure. In other cases the applications follow much later, as is true, for example, of the information learned about magnetic materials, which could be turned later to the design of better magnets for industrial purposes. Such a fundamental matter as the interaction between the neutron and the electron certainly has no practical application in the short run. However, even in this case we can well see that the fundamental information learned about the meson structure of the neutron can lead to better nuclear theory. This improved nuclear theory in turn would be of great benefit in predicting the neutron cross sections of materials needed for construction of reactors, but whose nuclei are still not well measured, or in fact may not even exist as yet in sufficient amounts for experiments.

Use of Neutrons for Medical Therapy

In the present chapter we are considering only the direct use of neutrons to attain a variety of ends, deferring to the next chapter their use in producing the widely used radioisotopes. Thus far, all our illustrations of direct use of neutrons have been restricted even further, for they refer only to basic research, in which no immediate practical objective was intended, but solely the discovery of the secrets of the structure of matter. The knowledge so gained, it is true, could at times be turned immediately to practical results, but these results were not obtained with the direct use of neutrons themselves.

We now turn, however, to a striking example of the way in which neutrons have been used directly to produce an immediate practical result, rather than to gain basic knowledge which perhaps could later be applied to practical objectives. It is interesting that there are so few examples of the direct use of neutrons for practical ends, essentially all of the direct neutron work to date being of fundamental research nature. The example we shall use, however, shows that direct use of neutrons can be very important. It is also a dramatic example of the things that can be done using the presently available intense neutron beams that did not exist before the chain reaction was discovered.

The example of the direct and immediately practical use of neutrons that we wish to describe is the so-called *neutron-capture therapy,* which refers to the direct use of neutron beams for the treatment of brain cancer. This treatment, still in the experimental stage, was developed at Brookhaven National Laboratory, and it has been used so far for treatment of a number of patients. Its success with these patients, and the possibilities for the future, are sufficiently encouraging that an entirely new reactor is now under construction at Brookhaven Laboratory, to be used primarily for research in the treatment of brain cancer with radiation.

In the treatment of cancer by radioactivity, which has already been in use for over 50 years, the principle involved is the destruction of the cancer cells by means of radiations, whether they be alpha, beta, or gamma rays. It is of course necessary in the treatment to avoid as far as possible the destruction of nearby healthy tissue, and the ideal radiation would be one that distinguishes between healthy and malignant tissue, affecting only the latter. In the particular type of brain cancer that is treated by neutron-capture therapy, the cancer cells absorb more of the chemical *boron* from the blood stream than do the healthy tissues. Thus if a boron solution is injected into the blood of a patient having this type of brain tumor the boron will deposit more quickly in the cancerous tissue than in the surrounding tissue.

Now boron has an extremely high absorption cross section for slow neutrons (which is why it is used in reactor control rods), and the boron nucleus, after absorbing a neutron, quickly gives off its energy of excitation in the form of an alpha particle. It follows then that if neutrons are passed into the head of a patient after injection of boron into the blood stream, the neutrons will disintegrate the boron nuclei, which are more plentiful in the cancer tissue, and the alpha rays so produced will destroy some of the cancer cells, with distinctly less harm to healthy tissue. It is because of the selective rapid absorption of boron by the cancer cells that the alpha particles produced kill these particular cells without causing intolerable damage to the healthy surrounding tissues. Complications arise because in order to make the treatment effective it is necessary to have a very intense beam of neutrons pass into the head of the patient. It is difficult, however, to obtain such a high-strength beam of neutrons without at the same time producing many gamma rays, which cause unavoidable damage to all tissues through which they pass. At the present stage of development of the neutron-capture treatment, a very intense dose of gamma rays is received by the patient. Improvements in technique will undoubtedly alleviate some of the present difficulties, but for some time to come the gamma radiation will present a serious obstacle to the widespread use of the method.

The method now in use for treating patients at the present Brookhaven research reactor is shown in Fig. 31. This arrangement is the best that could be made with the available graphite research reactor, and, while it is somewhat crude, it has given extremely encouraging results. The purpose of the large block of bismuth is to remove some of the gamma radiation, which might otherwise harm the patient severely. Bismuth has the useful property of allowing neutrons to pass through it practically undiminished but of stopping many of the gamma rays that always accompany the neutrons in a reactor beam.

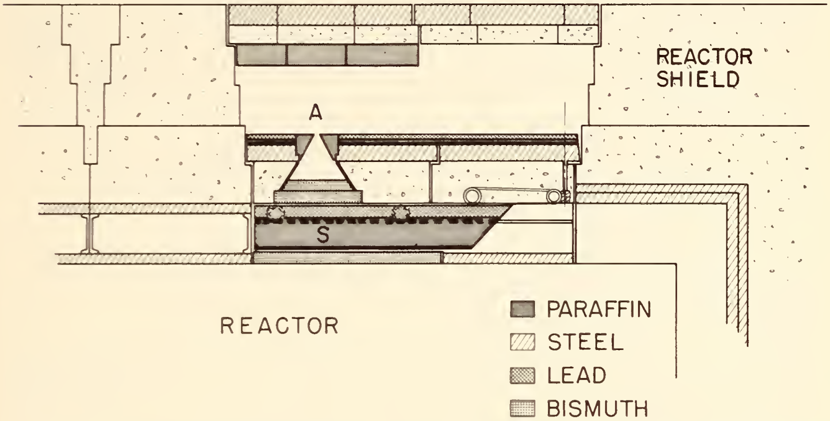


Fig. 31. The experimental arrangement used at the Brookhaven graphite research reactor for irradiation of brain tumors by means of neutrons, the so-called "neutron-capture therapy" that is described in the text. The equipment is placed in an opening in the top shield of the Brookhaven graphite reactor. The patient's head is located at the aperture *A*, where it receives a high neutron intensity when the shutter *S* is open. The gamma rays are reduced by the interposition of thick layers of bismuth in the beam.

The new Brookhaven Medical Research Reactor, which is now under construction, is shown in Fig. 32. Here the entire reactor was designed with the purpose of providing as high an intensity of thermal neutrons as possible without an accompanying intense beam of gamma rays. The number of neutrons entering the head of the patient will be about 25 times as great in the new medical reactor as it was in the equipment shown in Fig. 31, and the gamma intensity should be low enough not to produce harmful effects. A medical reactor is now being built in Los Angeles which will be used for similar treatment, as well as another at Massachusetts Institute of Technology, for medical and general research.

It must be emphasized that this treatment has so far been applied to only one specific type of brain tumor and that it is not a treatment that is on a routine basis as yet. However, the results show definite promise for the future and it seems likely that the new methods based on direct use of radiation will have a definite beneficial result in the long run.

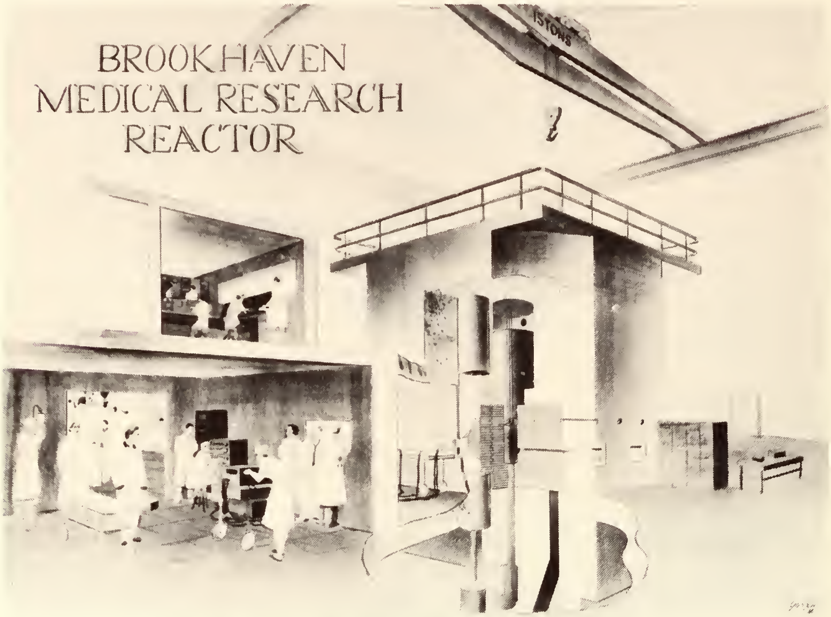


Fig. 32. The medical reactor now under construction at Brookhaven National Laboratory that is to be used exclusively for medical experiments. The arrangement for neutron-capture therapy for brain tumors is shown in use.

Other Practical Uses of Reactor Radiations

When neutrons are used directly, as we have been discussing in the present chapter, they are extremely potent tools for delving into the inner structure of matter. However, their use for practical objectives is somewhat limited as yet, almost the sole example being the neutron-capture treatment for brain tumors. Intensive investigation is under way at the present time to ascertain if reactors could be used for other specific practical irradiation purposes, such as the sterilization of food by radiation or the promotion of certain chemical reactions. None of these programs has progressed far enough, nor do the possibilities of success seem real enough, that practical programs could be instituted very soon.

The primary cause of difficulty in the use of reactors for these irradiation purposes arises from the combined nature of the radiations, gamma rays, beta rays, and neutrons always occurring together in the reactor. Food can be sterilized by the gamma rays with little production of residual radiation, but the neutrons cause the food itself to become radioactive when captured in various elements, hence possibly unsafe for consumption. Unfortunately, it is extremely difficult to separate the radiations, although present efforts may ultimately succeed. One possible approach is to remove the fuel rods from the reactor after a long period of operation and place them near the food to be sterilized. In that condition the fuel rods emit gamma rays, although with an intensity much less than that in the reactor during operation, but no neutron emission takes place.

It is certain, however, that for a long time the main direct use of neutrons, both inside and outside of reactors, will be in the manifold applications to furthering our knowledge of the basic structure of nuclei, atoms, molecules, and crystals. This limitation to basic research does not apply at all to the ultimate practical value of the work, for it is certain to be true again, as it has been in the past, that knowledge of the fundamental aspects of matter will promote the application of these findings to a great range of utilitarian goals. But the benefit to be derived from neutrons is not limited to these promises of indirect results in the future; the use of neutrons in reactors is already serving as a great boon to mankind through the myriad radioisotopes that can be produced. We now turn to a description of the way in which these radioisotopes are made and some examples of how they have come into active use.

CHAPTER 6

RADIOISOTOPES

> *In reactors tremendous amounts of useful radioisotopes are produced as byproducts. These are truly a great peacetime byproduct—perhaps most important of the atomic age.*
>
> —FROM *Isotopes—An Eight-Year Summary,* VOL. 7 OF *Selected Reference Material on Atomic Energy* (UNITED STATES ATOMIC ENERGY COMMISSION, AUGUST 1955)

We have already seen, in Chapter 2, how the nuclei of certain atoms are unstable, giving up their excess energy by emission of several possible types of radiation, alpha, beta, or gamma rays. These radioactive nuclei are heavier, hence contain more energy, than their stable neighbors in the periodic table of elements, and attain stability by emitting their excess energy in the form of radiation. In the chart shown in Fig. 6, the unstable nuclei, or *radioisotopes,* are those having either too many or too few neutrons for a given atomic number and they return to a stable ratio of neutrons to protons by emitting the appropriate radiation. Of the elements that occur in nature, in general only the heaviest, for example, radium, are radioactive. Bombardment with nuclear particles, however, now enables us to make radioactive forms of all existing chemical elements, the great variety of which is indicated by the open circles in Fig. 6.

The number of available radioisotopes is now so large compared to the few naturally occurring radioactive elements available some 50 years ago that an entire field of science and technology has developed around their use. The process of fission itself produces several hundred kinds of radioactive fission fragments and these constitute an important part of the radioisotopes that have been found useful in science and industry. In addition, almost every nuclear reaction results in a radioactive nucleus and, as the number of nuclear reactions is so great, there are usually several possible methods of producing any particular radioisotope.

It is somewhat of a paradox that the probable benefits to mankind from the use of radioisotopes, possibly much greater than the gains of atomic power as such, are much more difficult to describe than such an obvious matter as production of kilowatts. Actually, the great benefits to mankind to be derived from radioisotopes are difficult to describe simply because they *are* so widespread. They are so numerous that all we can hope to do is select representative samples. They will come from a wide variety of fields, ranging from the most basic research to the most utilitarian applications, and from small-scale experiments using a few atoms to gross applications in which amounts of radioactive material far greater than the present entire world's supply of radium are used.

The use of radioisotopes constitutes a completely new tool in research as well as in practical applications. The principle of this tool is not difficult to describe and to this task we shall turn our attention immediately after examining, in the next section, how radioisotopes are produced. Radioisotopes can be used in extremely small amounts, as *tracers* to investigate the structure and the behavior of matter in physical, chemical, biological, and industrial processes. Used in large amounts, the objective is to produce some *gross* change in matter, whether it is to kill cancer cells, to sterilize food, or to promote chemical reactions of industrial importance. By and large, the use of radioisotopes divides cleanly into these two types of endeavor, their small-scale use as tracers and the large-scale use to produce gross radiation effects.

The Making of Radioisotopes

We have seen that almost any nuclear reaction, including of course fission, can produce unstable nuclei, and hence is a possible source of radioisotopes. However, even though many nuclear reactions have been known since the thirties, radioisotopes really came into their own only after nuclear reactors had been built. The intensities of neutrons are so great in nuclear reactors that the quantities of radioisotopes available after their advent were thousands of times what could have been made with the nuclear reactions in such particle accelerators as cyclotrons.

The principle by which radioisotopes are made in a nuclear reactor is extremely simple for it consists usually of the capture of neutrons by the particular chemical element of interest, which is placed in the reactor in its normal stable form. Thus, if a particular radioisotope, for example sodium-24 (whose symbol is Na^{24}) is to be produced, ordinary stable sodium (Na^{23}) is placed inside the reactor, usually as a powder in a suitable container. As elemental sodium is a dangerous chemical to handle, it would probably be irradiated in the form of a stable chemical compound, for example, sodium chloride, NaC1, which is ordinary table salt. As the neutrons in the reactor pass into the sample of sodium, some of the sodium nuclei capture neutrons, each one thus becoming Na^{24}, the radioactive form of sodium. The longer the sample remains in the reactor, the larger the number of its atoms that will be transformed from Na^{23} to Na^{24}, provided the Na^{24} atoms do not disappear too rapidly.

The rate of disappearance of a radioisotope, which in the case of Na^{24} is not very rapid, is a very important matter in general. A moment's reflection will show that, as the neutron radiation in the reactor continues and as Na^{24} nuclei are thus produced at a uniform rate, the number of them will steadily increase until the disappearance of the Na^{24}, by its own radioactivity, becomes appreciable. In the case of Na^{24} a beta particle is emitted in the radioactive disintegration. Thus the ${}_{11}Na^{24}$ is converted into ${}_{12}Mg^{24}$ (magnesium), which has the same mass as Na^{24} but one more unit of positive electricity, this net change being caused by the emission of the one energetic, negatively charged beta particle from Na^{24}.

Of course, as the number of Na^{24} atoms in the sample increases, the rate of disappearance of Na^{24} atoms by radioactive transformation to Mg^{24} will also increase. It is fairly obvious that the chance of a particular atom of Na^{24} being transformed is independent of the presence of other Na^{24} atoms, hence that the number disintegrating at a given time is greater if the total number present is greater. Eventually the situation must be reached in which the number of Na^{24} atoms disappearing by radioactive transformation is just equal to the number being formed by capture of neutrons, and consequently the amount of Na^{24} present in the sample of Na^{23} will change no further. At this stage, which is called *saturation,* a dynamic equilibrium has been reached between disintegration and formation by neutron capture; further irradiation will not increase the amount of radioisotope present. The build-up toward saturation for Na^{24} is illustrated in Fig. 33; after about 40 hours the increase in the amount of Na^{24} is slow indeed. An important conclusion of our considerations is that the saturation amount of radioactivity is greater if the neutron intensity is higher. For higher neutron intensity the formation rate, hence the disintegration rate and the amount of Na^{24} present at saturation, must be correspondingly greater.

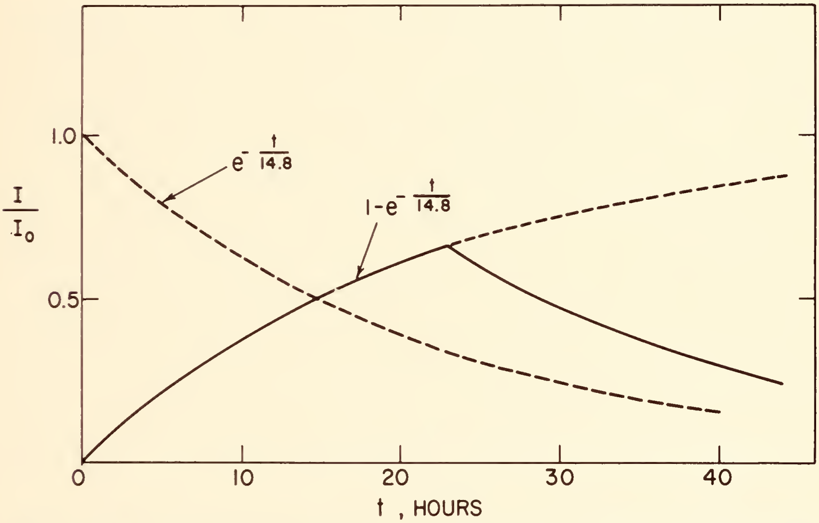


Fig. 33. The way in which the strength of a radioisotope, here sodium-24, of 14.8-hour half-life, increases as the sodium sample remains in the reactor. Plotted vertically is the activity I relative to the saturated activity, I_0. The curve starting at unity is the decay of a saturated activity starting at time t equal to zero. The manner of decay of the radioisotope after the irradiation ceases is also shown. The mathematical expressions shown with the curves describe the exponential behavior of the formation and decay of the activity.

When the sample containing the radioactive atoms is removed from the reactor, say after saturation has been reached, it will then decrease in *strength,* that is, in emission rate of beta particles, because the Na^{24} atoms are transforming into stable Mg^{24}, initially at a rapid rate just equal to the formation rate while in the reactor.

The chance of a given atom's disintegrating is independent of the presence of other atoms, hence the total number disappearing at a given instant will become smaller as the number of Na^{24} atoms decreases. Thus, as the total amount of Na^{24} present decreases with time, the rate at which atoms transform, or the strength of the radioactive sample, decreases correspondingly with time. This decrease of strength of radioactivity, in which the rate of decrease itself decreases with time, is called an *exponential decrease,* and is shown in Fig. 33, in addition to the manner in which the radioisotope increases during irradiation in the reactor. It is seen that the curve for disappearance of the radioisotope after removal of the sample from the reactor is merely the inverse of the curve that shows its build-up in strength during irradiation.

The rate at which the radioactivity decreases in strength, or *decays,* is a characteristic property of the particular radioisotope. It is generally true that the more unstable the atom, that is, the greater the energy of the particle emitted during disintegration, the more rapid is the decay. The rate of decay, or the instability of the radioisotope, is expressed in terms of its *half-life,* which is the length of time required for half the number of atoms initially present to disintegrate, being 14.8 hours for Na^{24}, for example. The decreasing rate of decay with time that we have just considered is well shown by the concept of the half-life itself: after one half-life 50 percent of the atoms remain, after another half-life 25 percent, then 12.5 percent, 6.25 percent, and so on. It is thus seen that the *rate* of decay decreases in just the way that the total number of atoms decreases, for the former must be proportional to the latter. The half-life, the measure of the stability of the radioisotope, varies from one material to another over a truly tremendous range. Radioisotopes are known with half-lives so short that they transcend our methods of measurement, being even shorter than one-millionth of a second. At the other extreme half-lives of radioisotopes transcend again our ability to measure them, some radioisotopes having half-lives greater than billions of years. Between these great extremes there are half-lives of seconds, hours, days, months, or years, and the great range in half-lives is of tremendous help in picking radioisotopes for specific applications.

It is indeed fortunate that the number of neutrons is so great inside nuclear reactors that quantities of radioisotopes sufficient to meet the ever-expanding demand can easily be made in them. It is of great importance also that almost all of the useful kinds of radioisotopes can be made by use of neutrons in the reactor. For radioisotope production with reactor neutrons, the typical reaction is neutron capture, such as we have described for the making of Na^{24}. In some cases, very few in number, other reactions, such as the type in which the neutron is absorbed and a proton emitted, the "(n,p) reaction," are also used to make radioisotopes. However, these other reactions can often be performed much better in particle accelerators, because they typically require fast neutrons. The main use of reactors, with their high intensity of slow neutrons, is to make large quantities of radioisotopes by the neutron-capture reaction.

It is not difficult in principle to obtain the specific radioisotopes from the reactor that are present in the radioactive fission fragments, for in that case it is necessary only to separate them after they are formed in the act of fission. This separation involves the removal of the metallic uranium fuel rod from the reactor, followed by isolation of the particular radioisotope of interest from the bulk of the fission fragments and uranium by a chemical separation. This method will obviously not work for a fission fragment with a short half-life, for the fragment will have decayed completely during the process of removal of the fuel rod from the reactor and the subsequent chemical separation. In certain important cases, however, fission fragments with half-lives of only a few minutes have been successfully isolated by high-speed chemical methods. Since chemical separation in the presence of the many elements occurring as fission fragments is rather complicated, fission fragments are not used as radioisotopes as commonly as those radioisotopes produced directly from the element of interest by capture of neutrons in the reactor.

A large selection of radioisotopes is made by neutron capture in the Oak Ridge reactor and sent throughout the world for use in various types of research. To illustrate the magnitude of the program, we may note that the Isotopes Division of the Atomic Energy Commission in the United States has made a total of over 80,000 shipments of radioisotopes produced in the Oak Ridge reactor, to users throughout the world, with less than 10,000 going to direct AEC installations. But the bare recital of numbers cannot give the true significance of the impact of radioisotopes on practically all branches of modern science, and we shall attempt to give an impression of this impact by examining for most of this chapter some of the important uses of radioisotopes. We shall see, for example, why radioiodine, I^{131}, used in so many forms of research and practical application, alone accounts for over 30,000 of the radioisotope shipments.

In producing the wide range of species of radioisotopes and the large number of samples of each species, it is to be expected that many problems must be solved in developing the methods of manufacture. From what we have already learned about the principles of operation of nuclear reactors, one of these difficulties should be immediately obvious. It is simply that if we try to make large quantities of radioisotopes or too great a variety in the reactor at a given time, it may well be that so many neutrons will be absorbed in the samples that the chain reaction simply cannot take place. Another way of describing this undesired situation is to say that the available *excess reactivity* of the reactor can conceivably be swallowed up completely by the manufacture of radioisotopes and the *reproduction factor* thus decreased below unity. However, it is fortunate that the available reactors have been increasing in number constantly, so that more and more sources are added to produce the ever-increasing number and variety of radioisotopes necessary to fill the rapidly increasing demand.

Even a bare listing of the fields in which the radioisotopes are used would be an impressive demonstration of this demand. However, it should prove to be a better approach to consider examples, drawn from several of the major fields of radioisotope use, that will well illustrate the way in which radioisotopes are used in basic research, development, and practical application.

Tagged Atoms—Radioisotopes as Tracers

Radioactive atoms, if used in all the ways speculated on in the press for the last few years, are about to revolutionize our lives completely. Our homes will be heated by small furnaces charged with fission fragments; we can do away with refrigerators because all foods will be easily and cheaply sterilized by radiation; and most diseases will vanish from the earth, their germs eliminated also by radiation. Here again, as for the case of atomic power, the sober facts are widely different from the unbridled speculations. Yet the truth, while it must deal with a longer time span for significance, is a remarkable promise of things to come through the radiations from atoms. As we did for atomic power in Chapter 4, we wish to devote our time and thought primarily to those things that have already been demonstrated, rather than to vague promises for the future.

And radioisotopes have abundantly demonstrated their potency for peace. The rapidly expanding use of radioisotopes has already carried them into practically every field of research, and they are spreading as well into development and initial applications. As the influence of radioisotopes moves from the stage of basic research to that of practical applications, so the actual amounts of radioisotopes involved increase from the few atoms that are used in basic research to the amounts required for practical utilization. These amounts are often so large that they are definitely lethal if careful safeguards are not invoked.

Guided by this progression from basic research to practical applications, we can first examine the way in which radioisotopes are used to gain information about the structure and behavior of matter, that is, the use of radioisotopes as *tracers*. We can then proceed to the practical utilization of radioisotopes in large amounts, the use of radioisotopes to produce gross effects. The progression, then, is from radioisotopes as a means of gathering information to their use to do something with the information so gained. At the present time by far the widest use of radioisotopes is in research and there, used as tracers, they give us information on the intricate details of the interior of matter, things that could be learned only with great difficulty, if at all, by previously used methods. The principles of the use of tracers are somewhat difficult to explain, partly because they deal with highly technical matters, which will not find application for many years, and partly as a result of the great variety, the thousands, of ways in which radioactive tracers are used, with the result that it is hard to think of simple unifying classifications.

For the second class of radioisotope use, to produce gross effects, the explanation is much simpler because the applications are usually dramatic and produce obvious, large-scale, easily described effects. Furthermore, the practical use is still limited to a sufficiently small number of fields that there is no problem of covering thousands of categories, as is true for tracers.

The basic reason why radioactive atoms can be used as tracers is that they emit energetic, easily detected radiations. The excess mass of a radioisotope relative to the mass of a stable nucleus represents energy, and by Einstein's equation the energy appears as energy of the radiations emitted, amounting typically to something like a million electron volts. The half-life of the radioisotope depends roughly on the amount of energy available; the greater the energy, the more rapid the conversion, and the shorter the half-life. Whereas the very heavy atoms often emit alpha particles, the usual radioisotopes emit beta and gamma rays. We recall that alpha particles are the nuclei of helium atoms, beta rays are high-speed electrons, and gamma rays are very short-wavelength electromagnetic radiations having no mass. The alpha and beta particles give up their energy rather quickly as they move through matter, causing greater changes in the material through which they pass than do gamma rays, but the latter penetrate much farther. As shown in Fig. 7, beta particles are typically stopped by less than 1 inch of solid material and alpha particles by even less, whereas gamma rays require several inches of lead in order to be absorbed. Thus gamma rays can pass completely through the human body, for example, with little attenuation.

The penetrating power of the radiations is one of the essential reasons why the atoms that produce them are so useful as tracers. A radioactive element, even though it is present inside a solid object, makes its presence known because the penetrating radiations emitted by it can be detected outside the object. Here then we see the meaning of the term *tracer,* for a small number of radioactive atoms, when mixed with ordinary atoms of the same element, reveal where that element is located by their radiations. In this way the element in question can be "traced" through practically any process by means of detection of the emitted radiations. The penetrating power of their rays, however, is only part of the reason for the tremendous utility of radioisotopes. Granted the penetrating power, the great potency of radioisotopes could not be utilized were it not possible easily to detect such minute quantities of radioactive tracers. Fortunately, it is actually possible to detect the radiation even from a single radioactive nucleus, the reason for this being the energy of the radiation and the extreme sensitivity of modern detectors of radiation.

Detection of Tracers

It requires only a brief comparison with heretofore available methods to illustrate the tremendous power of radioisotopes as tracers. For example, the usual methods of chemical analysis, even though highly developed through many years of research, still require the presence of an enormous number of atoms in order to detect a particular chemical element. For example, extremely sensitive chemical methods can detect an element when it is present in even as small an amount as one millionth of a millionth of a gram. But even this small amount would nevertheless be 10 billion individual atoms, if the element were sodium, for example. Yet this same element, if present as radioactive sodium, would make its presence felt even if only a few atoms are present, for one atom alone emits a penetrating radiation that can be detected with a modern nuclear counter.

The detectors of nuclear radiation should occupy a bit more of our time, for without these highly sensitive instruments the use of radioisotopes would be extremely limited. It is only because of them that significant studies can be made using amounts of radioisotopes sufficiently small that the radiations themselves do not change the object under study. For example, radioisotopes can be used in living tissues with no harm to the tissues, a fact which of course is possible only because radiations of individual atoms can serve as indicators of the radioisotope's presence. If it were necessary to use billions of atoms, as required for chemical identification, then the radiations would produce effects so harmful that the radioisotopes could hardly be used in living tissue, nor in fact in many of the delicate experiments where they are now used so successfully.

The nuclear detector that has made the whole field of radioisotopes a practical one is the well-known Geiger-Müller counter; the name is now almost universally shortened, perhaps unfairly to Mr. Müller, to "Geiger counter." The *Geiger counter,* shown in Fig. 34, is in actuality a rather simple device, which like many other tools of physics hides in its simplicity some highly complex phenomena, in this case the still not very well understood properties of electric discharges in gases. The counter itself is usually in the form of a cylinder, as shown, containing a gas, typically argon, and with a wire along the axis. A high electrical voltage is applied between the wire and the outer cylinder. The voltage is so high, in fact, usually about 1000 volts, that it is almost at the point of causing a spark or electric discharge to pass between the wire and the outer cylinder. However, as we know, atoms are usually electrically neutral, so the atoms of gas in the cylinder do not conduct electricity.

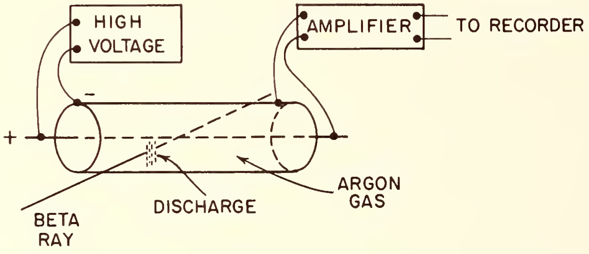


Fig. 34. The principle of operation of the Geiger-Müller counter; ionization in the gas within the counter produced by a penetrating particle causes an electric discharge, which is picked up by the amplifier and recorded.

In the absence of radiation, the Geiger counter is quiescent, and no spark passes. However, when a radioactive atom somewhere in the vicinity disintegrates and emits a radiation, say a beta or gamma ray, which passes through the argon gas in the counter, the situation is suddenly changed. Both beta particles and gamma rays have the property of removing some of the electrons from an atom, and the electrons thus removed constitute negative electric charges, whereas the affected atoms, short some electrons, will have a net positive charge. The negative electrons begin to move rapidly toward the central wire, which is positively charged, whereas the charged atoms begin to move slowly, because of their great weight, toward the outer cylinder. Then, by a rapid process of collision of the accelerating electrons with other atoms, thus removing more electrons, the amount of electric charge liberated increases rapidly. We shall not attempt to describe this process, not only because it is complex, but because its details still are unexplained in spite of much detailed research.

But skipping the details of the multiplication of charge, we nevertheless easily see that the amount of free electricity is soon so great that an electric discharge can pass between the wire and the cylinder. Once this discharge is produced, the rest of the detection is simple, for it merely involves the amplification of the electric signal or "pulse," resulting from the discharge, by electronic methods. The pulse of electric current passes along the wire and is picked up as an input pulse in an electronic tube, of the same general type found in radio or television receivers. This electric signal is then amplified in the same way a radio signal is amplified in a receiving set, to the point where it can make an audible click in a receiver or cause a signal lamp to show the arrival of the particle. Actually, in most experiments the number of rays hitting the Geiger counter is so great that the problem of counting them requires additional apparatus. Here the so-called *scaler* is used, an electronic device that counts the number of electric pulses and indicates the total number received by means of a system of lights or by printing the actual number on a slip of paper.

When pulses are being received at a rapid rate it is necessary to stop the electric discharge in the Geiger counter caused by one ray as quickly as possible so that the counter will be in condition to receive the next radiation. However, either by changing the voltage across the tube rapidly or by using certain vapors in it in addition to the gas, the discharge can easily be caused to stop after a few millionths of a second so that the tube is then prepared to respond to another impulse. Thus the Geiger counter can record many thousands of counts in each second and there is ordinarily no problem of its ability to handle signals at a rapid rate.

Although the Geiger counter remains the principal detector in the use of radioisotopes and does yeoman service, other instruments, in some ways even more stable and sensitive, have been developed. One type is just the same as the Geiger counter in construction, but uses a lower voltage and very highly sensitive electronic circuits so that the actual electric discharge does not take place but its mere beginnings are detected. As a result it is not necessary to wait for the discharge to stop to attain readiness for reception of the next signal. This second type of detector, the so-called *proportional counter,* can record rates even faster than the Geiger counter for those few applications when such extreme rates are encountered. The term "proportional" refers to the fact that the size of the electric pulse is proportional to the number of electrons released by the radiation, thus giving additional information of value concerning the ray passing through the counter. In the Geiger counter, the discharge mechanism produces the same size of electric signal regardless of the number of electrons originally released.

An even faster, and in many ways simpler, detector is now coming into common use, the *scintillation counter.* This detector is merely a piece of crystal, for example, a single crystal of lithium iodide, which has the property of emitting a tiny flash of light when a radiation, such as a beta or gamma ray, passes through it. This tiny flash of light can be detected by a *photomultiplier,* an electronic tube that can amplify the effects of extremely tiny pulses of light to the point where they can be detected electrically. This scintillation detector, which involves some mechanism inside the crystal that is still a long way from being understood, is by far the fastest type of detector, for its response involves merely the time required for light to travel from the crystal to the photomultiplier detector. In addition, it has the property, in common with the proportional counter, of giving a pulse proportional to the energy released by the radiation in the detector, in this case the crystal.

But lest we exaggerate too much the remarkable nature of the detecting instruments, it is best to point out that these latest types of instruments are not really necessary, though very useful, for the manifold uses of radioisotopes. The simple Geiger counter, as known and used for many years, could be used for practically all of the work, even though it might be a bit awkward or more time-consuming than the more recent detectors. The point we wish to emphasize is that it is not so much the potency of the equipment, but rather the inherent cleverness of the radioisotopes themselves, in their ability to make their presence known, that is the real source of the power, and the beauty, of tracer experiments. For it is the beauty of experiments using radioisotopes that the equipment is simple, and even inexpensive, on the scale of modern research, and this fact is a very important reason for the tremendous increase in the use of radioisotopes throughout the world. It is just because of the simplicity that experiments can be performed at small universities, which cannot afford the large machinery used in so many other forms of research. Likewise in hospitals, because only a simple Geiger counter and a few radioactive atoms are necessary, experiments can be done that add their little bit to the total knowledge being gathered by radioisotopes, which, taken as a whole, is accelerating the advance of science on many fronts at the present time.

Before considering in detail some of the ways in which tracers are used in various fields of research, let us summarize and illustrate the principles involved by describing how a tracer is used, without referring to the type of experiment at all, in order to emphasize the generality of the method. We have mentioned radioactive sodium before, so let us imagine an experiment in which it is desired to study the way in which the element sodium behaves in some unstated process. Ordinary sodium, we know, is Na^{23}, which if placed in a nuclear reactor absorbs a neutron and becomes Na^{24}, which lasts for a period of the order of 15 hours, its half-life. When the sodium sample is removed from the reactor a small fraction of its atoms will be Na^{24}, the rest of course still being Na^{23}. Because of the relatively short half-life, the experimenter will most likely not have this material sent to him from Oak Ridge, but would probably be working in the vicinity of a reactor so that he could receive the radioactive sodium within a few hours of its production.

He will then put the sodium into the material he is studying, which, because we do not wish to particularize, we shall call simply X. Should the material X be an animal, he would probably place the sodium in its food or inject it into its blood stream. If X is involved in a chemical reaction, he would simply include the sodium in the chemical ingredients, just as he would in the raw materials if he were studying the action of sodium in the manufacture of steel. The detection of the sodium, whatever the material X, is accomplished simply by placing a Geiger counter near X, as in

Fig. 35. The rate of signals in the counter, or the *counting rate,* gives immediately an indication of the amount of sodium that is near the counter. The location of sodium in X can be found without disturbing X by moving the counter around the object, the counting rate tells the amount of sodium that is nearby.

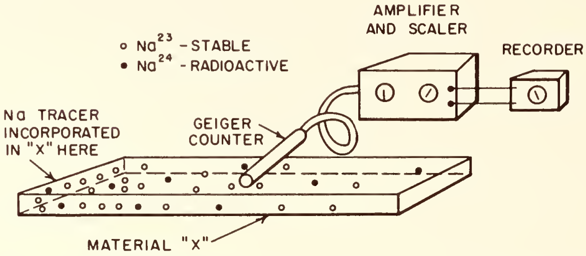


Fig. 35. The principle of the tracer technique as used in many experiments. The location of the radioisotope inside the material *X* is found without disturbing *X,* by means of the radiations detected by the Geiger counter.

If measurements are made as a function of time, it is possible to detect how the sodium moves through the material and what is its ultimate fate. In this way, even though the radioactive sodium atoms are small in number relative to the stable sodium in which they are dispersed, they act as a *tracer,* revealing the presence and the behavior of *all* the sodium. The tracer method is possible because the radioactive Na^{24} acts exactly the same as the stable or "normal" Na^{23} in all physical and chemical processes, hence gives an accurate account of the latter's behavior. The two isotopes, Na^{23} and Na^{24}, would of course act very differently in a nuclear experiment, but here we are considering only the usual atomic behavior. In certain experiments, rather elaborate methods are used to keep track of the tracer material as a function of position and of time. However, the essential simplicity of the method of radioactive tracers always remains—the counting rate is a direct measure of the amount of radioisotope, hence of the element under study, present in the immediate vicinity of the counter.

Complications do arise, of course, for example, that of distinguishing the radiations coming from the radioisotope from those originating from various other radioactive materials that might be present in the vicinity, usually called the *background counting rate.*

However, the rate of change of counting rate with time, which as we know is specific for the individual radioisotope, is often of great help in the identification. Also, we blithely refer to the "addition" of the sodium or other radioisotope to the material X, but in many cases the incorporation of the radioisotope into a complicated ingredient, such as the components of living tissue, is a formidable task. However, these latter difficulties are not insuperable and the illustrations we shall now consider will help to show how, in spite of many practical obstacles, radioisotopes as tracers are now contributing results of great significance in essentially all fields of research.

Tracers in Agriculture

It is well to begin our consideration of the use of radioactive tracers in research by describing some of the applications to agricultural science. The field is one with which we are all more or less familiar, and there are examples sufficiently simple and direct that it will be easy to grasp the mechanism by which tracers can be such a great aid in agricultural research. Of these applications, perhaps the most vivid are those with a direct practical effect, rather than those dealing with basic research, and we shall now look at a few of these practical uses of radioactive tracers in agriculture.

Even though the reasons are not fully understood, it is a well-recognized fact that certain elements present in very small or *trace amounts* (not to be confused with radioisotopes as tracers) have a striking effect on crops. The mechanism by which these elements get into plants, where they go in the plants, and how long they stay there, can be measured very directly and simply by adding these elements, containing a small fraction of radioactive atoms, to the soil. Counting-rate measurements, made with a Geiger counter held near various parts of the growing plant and the soil as time passes, reveal directly how long these trace elements stay in the soil, how they are carried into the roots, where they then go, and how long they remain in the plant. All this information follows directly, as described in the last section, from the quickly measured counting rate of the Geiger counter; here material X is the plant or the soil.

The immediate practical advantage of these measurements is obvious; the effects on the productivity of crops can be carefully correlated with the amounts of various trace elements that get into the growing plants. Furthermore, by placing the elements in the ground in various ways we can determine the best method for supplying these important elements, the best time to add them, and the correct amounts of trace elements to be used. It is easy to imagine how much more difficult it would be to get this precise type of information, if indeed some of the information could ever be obtained, by the conventional methods that had to be used before the extensive availability of radioisotopes, that is, by patient changes of conditions and long waits for many crops to learn the effects produced.

The information obtained by use of tracers in the way just described for trace elements is of great value in itself, and the same techniques are widely used to investigate the entire field of crop fertilization, a most important subject. The information thus gained makes it possible not only to increase the crop yield by establishing the results attainable by fertilizers, but also to reduce the cost greatly because highly efficient methods of fertilization can be devised on the basis of the results of the radioactive-tracer tests. These results are not mere speculation, for even though tracers have been used in agriculture for only a few years, the results of the findings have already been put into effect, and have led to increased crop yields and decreased fertilizer costs. The importance of these investigations is underscored when we realize that over $1 billion per year are spent for fertilizer in the United States alone.

It might be interesting to consider a specific practical result of these studies having to do with absorption of an important element, zinc, by fruit trees. It was found by use of radioactive-zinc tracer that absorption by the leaves was much more efficient than through the soil and that, even at below-freezing temperature, the sprayed zinc fertilizer would be absorbed and move several feet along a branch in a day or two. The practical application of these findings was soon made: dormant zinc spraying produced increased fruit yield the following season. In a similar way, radioactive phosphorus, P^{32}, has been used to give valuable data on the correct way to apply phosphate fertilizer; here again, the somewhat surprising fact was established that leaf absorption was much more efficient than root absorption.

In addition to the immediate practical matters of how best to get required elements into plants, there are the longer-term and more basic questions of how the life processes are carried on—how plants grow, make food by absorption of energy from sunshine, and reproduce. These basic studies are also greatly benefited by the use of tracers and, while the results are not so immediately obvious in dollars and cents, the understanding of the life processes in plants points the way also toward increased efficiency in agriculture. The study of root growth is an interesting example of these basic studies. By placing P^{32} at different points in the soil and checking the plant itself for radioactivity as a function of time, the actual growth pattern of the roots could be measured. The future practical application to fertilizer distribution hardly requires comment.

One of the most complicated processes that take place in living things is *photosynthesis,* whose secrets have evaded scientists for many decades. This is the process by means of which plants are able to combine water from the ground with carbon dioxide from the atmosphere to make food, using sunlight as the source of energy for the process. It is the carbohydrate thus formed that becomes available to mankind for food, to be again turned into energy when the food is oxidized in human tissues. The process of photosynthesis, in spite of intensive study, is still largely a mystery and this potent process for storing energy from the sun still has not be duplicated in the laboratory. Although the use of radioactive tracers, primarily carbon as C^{14}, has greatly increased our knowledge of photosynthesis, the process itself is so complicated that we are still a long way from the ultimate unraveling of all its secrets. Some of the important steps have been duplicated in the laboratory recently, however, based on tracer experiments. Continued use of radioisotopes is certain to expedite the whole research problem, one that has great portent for the future, for if photosynthesis could be understood and duplicated apart from plants it would be possible for man to store the energy of the sun as carbohydrate directly in large "food factories," without the intervention of plants.

Tracers in Biology and Medicine

The life processes in animals and men, both in health and in disease, provide many examples of the use of tracers to study the behavior of elements and compounds in otherwise inaccessible locations. In fact, the most common lecture demonstration of a radioactive tracer involves the speed with which sodium, after ingestion in the body, is circulated through the blood stream. This simple and effective demonstration is performed by the lecturer swallowing some salt water in which the salt contains some radioactive sodium, Na^{24}, in addition to the normal Na^{23}. By holding a Geiger counter near various parts of his body he can then show that within a few minutes the sodium contained in the water enters his blood stream and proceeds to all parts of his body. The time required for the Geiger counter to signal radioactivity when held near a given part of the body shows how long it takes for the blood to circulate to that point and the intensity of the radiation is a measure of the amount of sodium at the particular location.

This simple demonstration reveals the great potency of radioactive tracers in studying physiological processes. It is easy to see that this crude experiment can be made much more elegant, in order to study with precision the manner in which many important materials are taken into the body and are then assimilated. An example is furnished by the element calcium, so important to the formation of strong bones. It is easily realized how difficult it was, before the advent of tracers, to determine the way in which calcium gets into the body and how long it remains in various locations. However, it has now become possible to perform many such experiments, placing calcium in different kinds of food, feeding this to people of various ages, and by simple Geiger counter tests determining precisely how the calcium gets into the body. For example, the important matter of the entry of calcium into the teeth has now been thoroughly investigated using calcium tracer. The important question was, at what stage in the development of a human being does calcium enter the body and deposit in the teeth? This question, extremely difficult to investigate with former methods, was easily answered by means of radioactive tracers, using so few radiocalcium atoms that no danger to the subjects existed. It was easily found that calcium reached the teeth and remained there, not only during the stage when a young child's teeth are rapidly being formed, but throughout the entire adult life. The rate of deposition, as expected, was much greater for the children, but the adult assimilation was somewhat of a surprise.

A similar study, quite interesting and with obvious practical implications, concerned the connection between food eaten by chickens and the formation of eggs. Here it was found, again simply by adding radioactive tracers to the food and subsequent Geiger counting, that the eggs contained some chemicals from food eaten as much as 40 days before the egg was laid, whereas the shell itself represented much more recent acquisitions, actually three-quarters of the shell originating from food eaten the previous day. The applications of these and like studies to nutrition of human beings and animals is obvious, and their results are supplying valuable information on the correct feeding of chickens and children as well.

In addition to the thousands of studies concerning the normal operation of tissues in animals and man, there are many others being carried out on the malfunctioning of tissues in various diseases. A good example here is furnished by our first illustration in the present section, in which a simple experiment demonstrated the speed with which sodium was carried throughout the body by the circulation of the blood. A very important field of tracer research is concerned with just this matter—the way in which the circulation of the blood is impaired in various diseases. The investigations are performed by essentially the same method as our simple example, but refined greatly to obtain accurate quantitative results.

In connection with the study of blood circulation, an additional powerful radioisotope technique can now be described. Thus far, all of our illustrations have dealt with the simple matter of tracing a particular type of atom through some system. The versatility of isotopes, however, can now be shown in another application in which it is desired to measure the total volume of blood in the human body. Again, in analogy with so many tracer applications, it would be almost impossible to measure the volume of blood in a particular human being—but with a radioisotope tracer technique it is extremely easily done. A small volume of fluid (human serum albumin) containing some radioactive iodine (I^{131}) is injected into the blood stream and after this radioactive fluid becomes completely mixed throughout the entire body, which requires some 15 minutes, a very small amount of blood is withdrawn and its radioactivity determined with a Geiger counter. The strength of the radioactivity, after a simple calculation, tells exactly what the total blood volume is. For example, let us assume that the strength of the radioactivity in the withdrawn blood sample is just 0.1 percent of the strength of the fluid that was injected. It is then obvious that the original sample had been diluted by mixing with the blood by this same ratio. Thus the volume injected was 0.1 percent of the total volume of blood, and the blood volume is given simply by multiplying the volume of fluid injected by 1000. A dramatic application of this blood-volume measurement occurred in the Korean war, when it was used on the battlefield as a guide before administration of blood plasma. This *isotope dilution* technique can be used for many applications in which it is desired to measure a quantity of material in an inaccessible location.

One of the most important and difficult of the fields of research in the malfunction of living tissue is the study of cancer. Here we are not concerned with the use of large quantities of radioisotopes for the actual destruction of cancer cells, which comes later in our discussion, but only in the use of tracers for studying the mechanism of cancer growth. Today approaches are being made on a broad front, including many aided by radioisotopes, to investigate the basic mechanism of the uncontrolled growth of cells that constitutes cancer. Recently, for example, tracer studies have shown that there are definite differences in the metabolism of cancerous and normal tissue, that is, that the cancer cells require more of certain compounds to sustain growth than do normal tissues. These findings raise the possibility that advantage can be taken of the specific needs of cancer tissue for these compounds, where they differ from normal tissue. It might be possible to prevent growth of the cancer by depriving it of the material necessary for its growth, without destroying the normal tissue. The entire field is beset with extreme complexity and these studies are only beginnings in the understanding of normal and cancerous growth of tissues. They represent the type of research that is basic, in the sense that practical applications do not follow immediately, but that may eventually lead to results of importance impossible to estimate at the present time.

Another excellent example of basic research, recently aided by tracers, that promises important future results is the study of the action of insulin in the body. Insulin is the hormone secreted by the pancreas that is vital to the metabolism of glucose, the impairment of which results in the disease diabetes. Results so far, using tracer insulin, have shown that the entire metabolic process is extremely complicated, a substance known as "insulinase" being found in the blood that destroys insulin and still another substance, a liver enzyme, that stops the action of the insulinase. There seems to be a distinct, but not immediate, possibility of improved diabetic treatment based on these new findings.

There is a particular use of radioisotopes as tracers that is not actually research but rather an important aid to treatment of disease. However, because it is a use of the tracer technique rather than the gross use of radioisotopes, we shall mention it briefly here. Its development was made possible because cancerous tissues absorb certain elements much more readily than normal tissues. Thus it becomes possible to locate tumors by taking advantage of this preferential absorption. An example is furnished by the preferential absorption of iodine by brain tumors. Here the I^{131} is injected into the blood stream and is absorbed by the brain tumor, and detection of the gamma rays from the I^{131} with a small Geiger counter allows the shape of the tumor to be determined. The purpose here is to serve as a guide for surgical removal of the tumor, and such methods can even be used during the operation itself.

The problem of locating tumors for surgical removal is sometimes almost impossible because an original tumor may spread through the body and the cells start growing at places where they normally would not occur at all; these secondary growths are called *metastases.* Radioactive iodine, I^{131}, is used for location of such growths in the case of thyroid cancer because of the great affinity of thyroid tissue for iodine. The iodine is injected into a patient before an operation and the gamma radiation reveals the presence of malignant thyroid tissue wherever the metastases occur. An apparatus that automatically "scans" the entire body and actually draws a picture of the location of the I^{131} tracers, hence of the metastases, is shown in Fig. 36. With this pattern as a guide, the surgeon can locate the exact position of the cancerous growth and accomplish the surgical removal of the cancer.

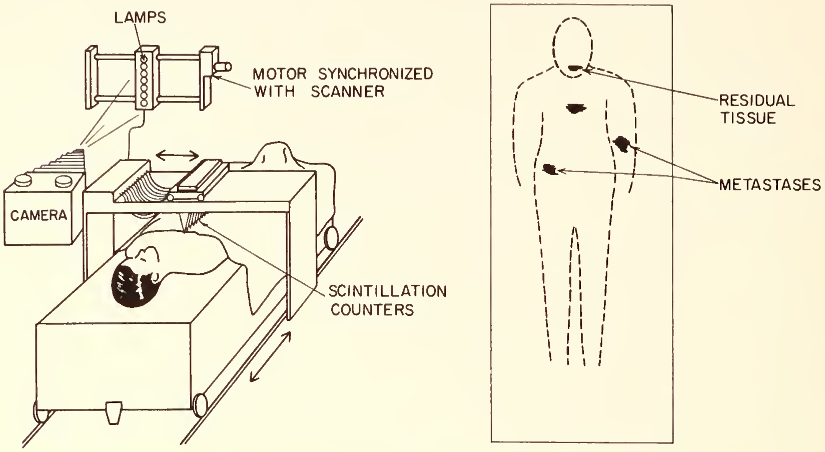


Fig. 36. The manner in which tumor tissue is located by means of the radioisotope I^{131}. The injected I^{131} deposits selectively in the tumor tissue and the radiations are detected by a scintillation counter, which then makes an impression on the photographic plate.

We have mentioned several times that the chemicals or compounds of interest, containing tracers, are injected into the body, put in food, or otherwise placed in the material under study. We have, however, so far neglected to mention the great difficulties that often occur in these experiments when it is necessary to place the radioactive atoms in a complicated compound. In some cases, the chemical elements, made radioactive in a reactor, can be put into the required compound by ordinary chemical processes. Often, however, the compound may consist of complicated biological molecules, each containing thousands of atoms, which simply cannot be made in the laboratory, that is, cannot be *synthesized* from their constituent atoms. These large biological molecules can usually be obtained only from actual living material, perhaps plants or animals. Thus there is no recourse but to "make" the compounds by natural processes, in the plants or animals themselves, using radioactive raw materials. This kind of manufacture is now being carried out in so-called *"isotope farms,"* in which various plants are grown, using radioactive fertilizer, water, or carbon dioxide. The plants then make tissues in the normal manner, with no alteration in structure resulting from the fact that the products contain radioactive atoms. Of course, short-lived radioactive elements cannot be utilized in this manner, for they would decay long before the normal processes of growth had produced the organic compounds desired. The tissue made by the plants can be fed to animals, who then synthesize the complicated biological compounds in their bodies, and these compounds again contain the particular radioisotopes originally supplied to the plants. For isotopes that are sufficiently long-lived, such methods can produce many intricate compounds, containing tracer atoms, that are of great value in biological research. Thus as time goes on, scientists will have available to them an increasing variety of tracer organic materials that cannot be made directly in the laboratory. These will be of great value in studying the basic life processes of living tissue in health and disease.

Tracers in Industry

The use of tracers in industrial research has started somewhat later than in the biological sciences, but at the present time the applications of tracers are multiplying rapidly in many branches of industry. Already, according to a recent survey of the AEC, radioisotopes are effecting industrial savings of about one-half billion dollars annually. One of these uses supplies a striking example of the great sensitivity of tracers in supplying results almost immediately that had required months of patient work by older methods.

This example comes from an extremely important field of industrial research, and one in which tracers may well revolutionize an entire section of industry. This field of research has to do with the question of wear, and in particular the wear of cutting tools used in various machining processes. Before the use of tracers the only way to study tool wear was simply to use the tool for such a long time that a significant part of it had been worn away. If it was desired to study the effect of various slight changes in the properties of the tool, such as the constituents of the tool steel used for its manufacture, months of patient study would be required to get significant results.

Now, however, the measurements are made simply by irradiating the tool in a nuclear reactor so that some of its atoms become radioactive. The tool is then used in whatever machining operation it is destined for and the amount of wear of the material of the tool can be detected almost immediately. The detection is accomplished by studying the radioactivity of the small chips of metal removed by the tool during the machining operation. The sensitivity is so great that the radioactivity worn off the tool and deposited on the chips can be determined after only a few seconds of machining, instead of the weeks that would otherwise be necessary to produce appreciable wear of the tool itself. Even the precise location on the individual chips of the atoms worn off the tool can be measured so that the exact mechanism by which the tool wears away can be thus determined.

Similar studies are being made of another important type of wear, that of piston rings in automobile engines, and the method is essentially the same. The piston rings are made radioactive by putting them in a nuclear reactor for several weeks and are then placed in a test engine. The wear of the rings can be detected after only a few seconds of running by measuring the radioactivity produced in the lubricating oil. Thus very quickly the effects on rate of wear of different types of oils and different constituents in the metal of the piston ring can be determined precisely. The cost of these studies is only 2 percent that of methods previously used. It is obvious that the wear of any moving part of an automobile, or of any machine for that matter, can be measured by utilizing the same principles.

The subject of wear of tools, gears, and all moving parts in industrial processes is such an important matter that it may well be that the largest gains from atomic energy, considered in terms of money alone, in the next few years may well come from this field alone. The amount of money spent in the United States on machining operations alone, that is, the cutting of metals in lathes, drill presses, shapers, and so on, amounts to about $10 billion per year. If improved design and methods of machining resulting from the use of radioactive tracers could effect just a 10-percent saving in this machining bill, the amount of money saved per year would thus be $1 billion, a truly impressive result of the practical use of radioisotopes.

We have not as yet mentioned one of the most important forms of wear, so familiar to all of us, namely, the wear of automobile tires. It can be taken for granted that an impressive amount of research is now under way concerning the fundamental processes involved in the wear of tires. After our previous examples, it now hardly seems necessary to describe how this research is carried out. It is obviously done by incorporating radioactive material in the tire, then measuring the radioactivity as it is deposited on the road surface against which the tire runs. Here again the wear can be measured quantitatively almost immediately without any necessity of extensive fleet tests, which constituted the only previously available method, involving many tires and months of running in order to reach significant conclusions.

In reference to the isotope farm, already mentioned, it is interesting to point out that rubber containing radioactive atoms has been produced by growing the rubber trees in an atmosphere containing radioactive carbon dioxide. This natural rubber containing tracer atoms will then be used to study the details of the treatment undergone by rubber in the various industrial processes in which it is used. These studies will deal with the basic mechanism of the complicated changes undergone by the rubber molecule rather than such a simple thing as the rate of wear on an automobile tire. But again, these basic studies, using rubber from the isotope farm, may well lead to a superior rubber for improved automobile tires.

It is in industry more than in any of the other fields that the routine or applied use of radioisotopes is advancing apace, as contrasted to their use in research. We refer to the vast field of *industrial control,* and it is here that radioactive materials show their extreme versatility and are already effecting savings estimated at more than $100 million a year. The great advantage of radioactive tracers is that they can be used as controls for industrial processes and to give information on the way in which the details of a process are working, without stopping the process itself for removal of samples and subsequent chemical analysis, as was necessary before. The measurements can be made instantaneously and the process can be continuously checked and adjusted without loss of time.

The widest application to date of radioactive materials to industrial control is in the *thickness gauges* that are used to control the many industrial products that are manufactured in the form of thin strips, for example, various kinds of metals, plastic, paper, and so on. The principle of a thickness gauge, illustrated in Fig. 37, is that a radioactive isotope is placed on one side of a film of material and on the other side is located the detector, which is a Geiger counter or scintillation counter. The intensity of radioactivity detected by the counter is affected directly by the thickness of the film, and this thickness can be measured instantaneously from the counting rate without stopping the movement of the film of material. Measurement of the thickness is just the first step, for in all such industrial processes the "reading," that is, the intensity of the radioactivity detected by the counter, is used to adjust the machinery to keep the film at a constant thickness, as shown in Fig. 37. If the film thickness should decrease slightly, the intensity of the detected radiation increases correspondingly and this increase in signal strength is used to adjust the process in such a way that the film thickness is brought back to its correct value.

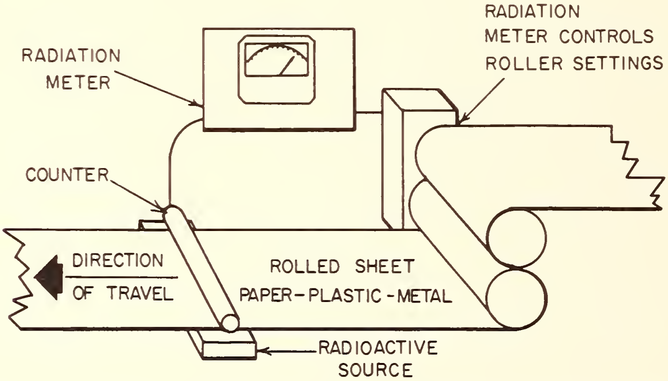

RADIATION METER
RADIATION METER CONTROLS ROLLER SETTINGS
COUNTER
DIRECTION OF TRAVEL
ROLLED SHEET PAPER-PLASTIC-METAL
RADIOACTIVE SOURCE

Fig. 37. The principle of operation of a thickness gauge utilizing a radioisotope.

To bring this industrial control matter close to home we can describe briefly the use of a thickness gauge in controlling the amount of tobacco in cigarette manufacture. Here the thickness gauge is placed across the stream of tobacco as it enters the paper cover to form the long cylinder that is then cut into individual cigarettes. The intensity of radioactivity measures the amount of tobacco in the long cylinder, hence the firmness of the cigarette. The amount of the tobacco can be determined instantaneously and, as we have already described, controlled by the strength of signal to keep a constant thickness. This can be done with great accuracy and rapidity, with the somewhat astonishing result that the weight of the cigarettes, which is proportional to the amount of tobacco in them, can be held constant to an accuracy of only 0.2 percent. The thickness gauges are so effective in this application that practically all cigarette factories now use them for standardizing the amount of tobacco in cigarettes.

Another general type of industrial control that can be performed by radioisotopes is the measurement and control of the degree of mixing of various liquids. In many industrial processes it is necessary to mix large quantities of different liquids and to do this as quickly as possible in order to attain maximum efficiency in a continuous process. The degree of mixing can easily be measured if a small amount of radioactive tracer is added to one of the components and a counter placed in the vessel where the mixing takes place. Constancy of the reading of this counter then means that the liquids are uniformly mixed. The use of tracers to study the degree of mixing can be applied both to the study of the mixing process, hence as an aid of the design of the process machinery, and to the continuous control of the process while it is operating. This type of mixing control is very important in the large-scale petroleum industry, particularly in the "cracking" of large molecules to produce the great variety of petroleum products that is now available. In this application the use of tracers is particularly advantageous because the readings are immediate, hence a minimum of time is lost in correcting departures from ideal conditions.

Because of the sensitivity of the detecting instruments used in the applications we have described, the amounts of radioactive tracer are so small that no danger is involved as far as the personnel in the plant are concerned. Moreover, it is possible to pick radioactive tracers of different decay times, so it is usually no great problem to select a tracer with a short enough decay time that by the time the product leaves the plant the radioactivity has completely died away and no possible danger remains.

Medical Treatment with Radioisotopes

We have already seen that the radiations from unstable nuclei, although able to penetrate rather large distances through matter, do not leave the matter completely unchanged when they do so. Some electrons are removed from atoms through which the radiations pass, and in fact it is these atoms, left electrically charged, as well as the electrons removed from them, that enable the radiations to be detected in counters. It is not surprising, then, when sufficient quantities of radiation are present, that the destroyed atoms, if present in sufficient numbers, can cause detectable changes in matter itself. When radiations are used in such intensities we usually speak of them as producing *gross effects,* as contrasted with the use of tracers where the intensity is so small that no appreciable change in matter itself is produced.

While the use of radioisotopes to produce gross effects is still limited compared with the widespread uses of tracers, the large-scale use of radioisotopes is an ever-increasing field. Much remains to be learned about such use, and much must be done to insure complete safety in the handling of large amounts of radiation, but it seems certain that in the next few decades the use of large sources of radiation will increase rapidly. We could speculate on many possible gross uses of radioisotopes, but in this and the next section we shall consider two of the most important of these uses, two fields in which rapid progress is being made at present. The first of these, the use of radioisotopes for treatment of disease, is an application that has been underway actually for about half a century, although the greatly increased supply of radioisotopes that we now possess has enlarged the scope of treatment by radioactive materials tremendously. The second, radiation sterilization of food, is an extremely new application but one of great potential benefit.

It is not surprising that the radiations which can tear atoms apart cause harmful effects on living tissue when the intensity is high. The radiations can actually kill the cells of living tissue, and, when a sufficiently large number of cells are killed, significant changes are produced in the particular tissue being irradiated. There are two sides to the destructive effects of radiation on living tissue, the harmful effects produced when human beings are exposed to unwanted radiation, and the beneficial effects resulting when some malignant tissue is purposely destroyed. It is this latter matter that we are concerned with at the moment, deferring the discussion of unwanted radiation until a future chapter. The most dramatic use of radioisotopes is to destroy cancerous tissue in the human body and, while the success of the treatment must not be exaggerated, it is sufficiently encouraging to hold definite hope for the future.

Actually, for many years the naturally occurring radioactive materials, such as radium, have been used for treatment of cancer. However, the limitation of treatment to only a few particular chemical elements, and furthermore very rare and expensive ones, was a severe handicap in the development of the method. Still other disadvantages were unfortunately associated with radium treatment. Radium cannot be taken into the body with safety for it deposits itself in the bone marrow and causes cancer of the blood-forming tissue in the marrow. The great penetrating power of the radium gamma rays implies that it is difficult to irradiate a particular organ without destroying nearby healthy tissue as well.

The contrast between the period before the advent of atomic energy and the present with regard to radiation treatment is truly striking, for now *every* element can be made radioactive by placing it in the chain reactor and it is then available as a possible source for treatment of disease. The advantage is not only that large quantities of radioisotopes are available, and at low cost, but that there is such a tremendous range of radioactive and chemical properties available from which to choose. Some radioisotopes live only a short time, hence they can safely be placed in the body because the radioactivity soon dies away; some have appropriate chemical properties so that they deposit preferentially in certain organs of the body and thus concentrate the radiation effects. Because radioisotopes emit a great variety of radiations, a particular type of radiation, such as one of low penetrating power, can be chosen to give a desired effect. This wide range of properties is reflected in a great variety of methods of treatment, which we can best illustrate by a few of the many available examples.

The principle of selective radiation is well exemplified by the treatment of thyroid disease with radioactive iodine. Iodine, when taken into the body, is deposited predominantly in the thyroid gland, most of the ingested iodine finding its way to the thyroid and not remaining in any other tissue of the body. In hyperthyroidism, or overactivity of this gland, it is desired to destroy part of the thyroid. This destruction can be done easily by administering iodine, made radioactive in the reactor, to the patient. The ingested radioactive iodine deposits in the thyroid gland and its radiations destroy some of the cells of the thyroid gland without affecting other tissues of the body. Furthermore, the radioactivity of the iodine dies away after a few days so that continued irradiation does not occur as it would if radium were to be placed inside the body. This method of treatment is now sufficiently well established that it has been used in tens of thousands of cases.

Another example of the selection of a particular element because of a useful specific property is furnished by the use of radioactive phosphorus in the treatment of skin cancer. Radioactive phosphorus is unusual in that it emits beta particles only, no gamma radiation being produced. Because beta particles have such a short range in matter, as shown in Fig. 7, the radiations from phosphorus affect only the material very near the radioactive source. Thus to treat cancer of the skin, radioactive phosphorus is spread on the skin itself in a thin layer; the beta rays from the phosphorus go into the skin and kill some of the cells, but do not penetrate through the skin and affect the underlying tissues. Radium, if used in this way, would affect all the tissues under the skin as well as the skin itself, because of the great penetrating power of its gamma rays. Radioactive phosphorus can also be used to irradiate the lining of the stomach by putting it in contact with the stomach wall, and no danger exists for other nearby tissues. In this treatment the phosphorus is spread on the outside surface of a rubber balloon, which is swallowed by the patient, and then inflated.

These examples illustrate the possibilities for treatment of disease by selection of radioisotopes with desired properties. We must be careful not to intimate any universal applicability of this approach, however, for it is not at all easy to find a chemical element that has the desired properties. Ideally, the material must irradiate a particular tissue, perhaps deep in the body, without harming other organs, even a short distance away. Much research, however, is being concentrated on the search for suitable elements and for new techniques of irradiating specific tissues, and it is certain that the selective-absorption method will be extended by the results of these efforts.

Radioactive cobalt is now widely used in the treatment of cancer, not in the highly selective way just described, but in a manner somewhat similar to that in which radium has been used, that is, held *near* the tissue or organ of interest without actual absorption in it. The use of radiocobalt is of great importance, however, even if used in this imperfect way, because it can be produced in such large quantities and at very low cost. As a result the availability for widespread treatment is greatly increased over that of radium.

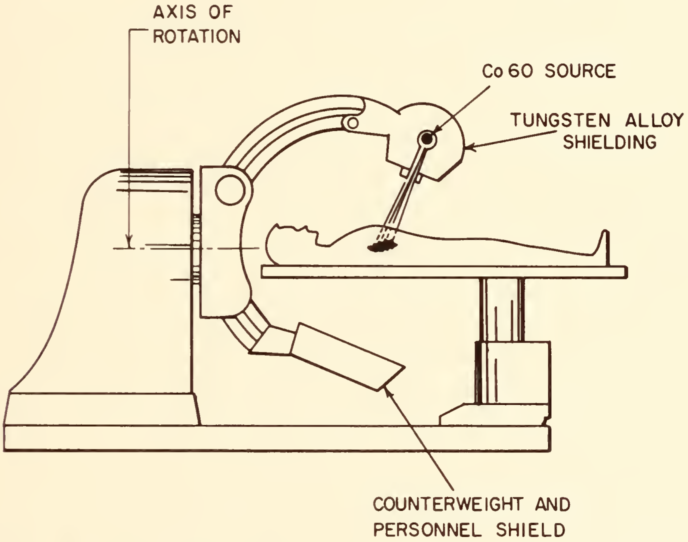


Fig. 38. A teletherapy unit, in which a strong source of radiocobalt is used for the irradiation of cancer with minimum harm to surrounding healthy tissue. The apparatus is rotated around an axis through the tumor, so that healthy tissue receives only a relatively small amount of radiation while the tumor is constantly irradiated.

Sources of radiocobalt have actually been made in high-flux reactors for treatment of cancer that have strengths equivalent to all the radium that exists in separated form in the entire world. It is of course necessary to build large shields for protection of personnel for these high-strength sources, and to direct the rays from them by suitable channels so that only the desired parts of the body receive the radiation. Such an installation, called a *teletherapy unit,* is shown in Fig. 38. In this arrangement the entire source holder rotates around the patient so that the beam of radiation produces a concentrated effect in the desired organ, while minimizing the damage to the surrounding tissues.

Radiation Sterilization of Food

Of the various ways in which the gross effects of radiation might be turned to useful purposes, some are already being put into practice, others seem likely in the near future, whereas others are still far from practical application at the present time. One field of endeavor, in which some beneficial results are just beginning to appear, is the production of new strains of plant life by radiation-induced mutations. However, because most of the radiation effects are harmful we shall not dwell on this subject at the present time but return to it briefly in Chapter 8, where we shall consider the broad field of radiation effects on heredity, both harmful and beneficial. Another possible gross effect is the production of chemical changes by intense radiation, but this is a field that, while it shows some promise, has no practical applications at present. The example we wish to consider, and one that may have wide significance, is the sterilization of food by irradiation. Extensive experiments have shown that food can be sterilized, primarily by means of gamma radiation, without producing radioactivity in the food itself. Gamma radiation is much better for this purpose than neutrons, for neutrons produce extensive radioactivity in all materials that are bombarded. Sterilization produced by neutrons would not be practical unless the radioactivity could be removed, because of the danger of eating radioactive material.

Of course one factor that must be kept in mind in connection with radiation sterilization is the cost involved, for if the cost should be as high as several cents per pound the process would not be economically feasible. Even if it were uneconomical, however, the process might nevertheless find some useful application in special circumstances, for example, in military operations, where cost is not a primary factor.

There are various ways in which the gamma radiation might be produced at prices that are not too high. One of these is to use fuel rods from reactors after they have been removed from the reactor. This removal is necessary, for example, when so much of the U^{235} has been used that the fuel can no longer maintain the chain reaction. Because of the large amounts of fission fragments present in the fuel rods at that stage they emit extremely high intensities of gamma rays, but no neutrons. These *spent fuel rods* can be used as by-product sources of gamma radiation with very little additional expense beyond that connected with the operation of the reactor itself. This situation implies that it might be possible to assign all production costs of these gamma sources to reactor operation. It has recently been announced by the Atomic Energy Commission that spent fuel elements from the Materials Testing Reactor at Arco, Idaho are available for rental at $100 each per year. As the available number is small, however, each user will be limited

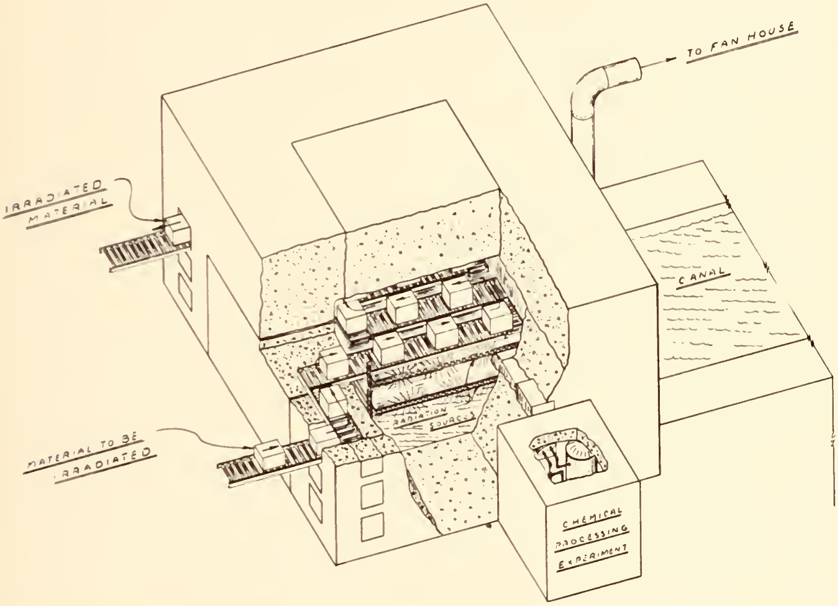


Fig. 39. A suggested method by which food could be sterilized by passing it near sources of gamma radiation, here shown as fuel rods from a reactor containing fission fragments. The fuel rods are moved from the reactor through the water-filled canal to avoid radiation hazard.

to four elements. Another method of manufacturing sources of gamma radiation is to produce radioactive cobalt by irradiation in reactors, and then place the cobalt samples in a geometric arrangement designed to give as high an intensity of gamma radiation as possible. Actually, whether spent fuel rods or radiocobalt are used, the arrangement for irradiating articles of food would be about the same. Figure 39 shows a typical suggested arrangement in which the food to be sterilized would be carried on a conveyor belt past the fuel rods or radiocobalt sources, which are kept in a heavily shielded room.

Tests that have been made so far have shown that it is possible to sterilize fresh meat so that it keeps without refrigeration for several months. Unfortunately, even though the sterilization works well, the volunteers who have eaten such radiation-sterilized meat report that the taste suffers a real loss. The advantage of being able to keep perishable foods indefinitely without refrigeration is so great, however, that intensive research is being devoted to all phases of the problem at the present time. If it were possible to sterilize the perishable food inside a nuclear reactor the method might be made much more practical and of lower cost. However, the simultaneous presence of neutrons with the gamma rays in a reactor, and the resulting radioactivity in the food, provides a serious obstacle. It has recently been announced, however, that a reactor will be designed and built for the U. S. Army in an effort to develop suitable shield arrangements to separate the neutrons from the gamma rays so that the reactor might be used for radiation sterilization without producing prohibitive amounts of radioactivity. Eleven industrial firms made proposals to participate in this endeavor, in spite of the obvious difficulties, and the "Sterilization Reactor" is to be built by the Kaiser Company at Stockton, California.

CHAPTER 7

THE INTERNATIONAL ATOM

The agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health, and prosperity throughout the world.

—FROM THE STATUTE OF THE INTERNATIONAL
ATOMIC ENERGY AGENCY,
ADOPTED OCTOBER 23, 1956,
UNITED NATIONS, NEW YORK.

Thus far we have devoted practically all our attention to the many ways in which atomic energy is already proving to be a benefit to mankind, by means of power, basic research, and radioisotopes. We have also intimated how in the future these benefits may grow beyond our present contemplation, provided of course that man handles atomic energy correctly, that he learns to live with it rather than let it destroy him. So it is appropriate that we again contemplate the two-sided aspect of atomic energy, its use for war and peace. Since describing at the outset how these two phases develop together and in practice are inseparable, we have not returned to the destructive aspects of atomic energy but have concentrated only on the beneficial applications, which are already proving to be of so much value in our own lives.

But we cannot neglect the negative aspects of atomic energy completely. If they are to manifest themselves, if we are to have a world-wide conflict utilizing A- and H-bombs, then all the gains that we have already realized, as well as the potentiality of many more, could be wiped out by one enormous conflict. The destructive phases of fission and fusion energy are practically completely involved with their use as military weapons. There are of course dangers involved in the use of atomic energy, even when destined only for peacetime pursuits, but these dangers are more a matter of industrial safety, though extremely complex, and we shall postpone our concern about them until the next chapter. The vastly more important dangers arise from the possibility that atomic energy will be utilized as a military weapon with resulting havoc almost beyond our power to visualize.

While it is not our purpose to deal with the destructive aspect of atomic energy, with its use as a military weapon, or with all the complex factors involved in international control of bombs, it is completely appropriate that we look at the international aspects of the peacetime atom. The emerging world-wide coöperation in peaceful uses of the new power may in fact be the most important factor in controlling atomic war. Considered on the level of physical well-being alone, international coöperation in atomic energy deserves the careful attention of all because of the great possibility for material gains throughout the world. However, from another aspect, a thorough examination of this coöperation attains added significance. The increased importance stems from the very definite possibility that the entire "atoms for peace" concept, the coöperation on an international scale for the betterment of man, can move rapidly ahead, unhampered by existing organization. Thus it may very well be that the coöperation attained in this new field can serve as an example for similar joint efforts in other activities, the net effect of all being an increase in mutual trust among nations.

Thus "atoms for peace" might signify not only "atoms for peacetime uses" but "atoms for the attainment of peace." The unofficial motto of the Geneva Conference in August 1955, "atoms for peace," was displayed prominently in the exhibits of all nations. Our present thought is well illustrated by the Russian form of the phrase, which, literally translated, emerged as "atoms *make* peace." This possibility is real, and increases greatly the importance of the present rapidly developing international aspects of atomic energy. The conversion of mass to energy may not only supply the means for a full life for all men, but help them to live it in peace and understanding.

Our program then will be to discuss in the present chapter the international coöperative efforts in the peaceful pursuits of atomic energy, with particular attention to the great flowering of this coöperation in connection with the Geneva meeting. In the following chapter we can then turn to the dangers inherent in atomic energy, dangers that are present both in peacetime atomic-energy efforts and in their use as military weapons. Finally, we shall look at the distant future, at the possibility of attaining useful power from the process of fusion, the mechanism involved in the explosion of the H-bomb. The problem of turning the H-bomb to peacetime pursuits involves many of the thorny questions relative to international effort, for fusion is largely still a military secret, and the question of the relative position of various countries and the resultant effect on security has a great significance at the present time.

International Atomic Energy Before Geneva

In order to understand the present rapidly expanding international coöperation in atomic energy, it is very useful at first to remind ourselves of the atomic situation before the Geneva Atoms-for-Peace Conference, and what led to the conference itself. Actually, atomic energy as a matter of world importance is a newcomer. In 1945, the world was made aware of atomic energy by one blinding flash over Hiroshima. Many scientists, however, had already lived with the secret for three years, since the successful release of atomic energy by means of a nuclear reactor in December 1942. And now, only some dozen years after the world's knowledge, and a few more since the more appropriate birth date of controlled nuclear energy, the large-scale gains to mankind, so eagerly prophesied in 1945, are at last emerging.

In this connection the morning of January 17, 1955 seems to possess a particular significance. For on that Monday morning, scientists of five countries gathered to discuss an agenda for the United Nations international conference on peacetime atomic energy, scheduled for August of that year. Just as their meeting was taking place in the United Nations building in New York City, the submarine "Nautilus" was heading into Long Island Sound one hundred miles distant, signifying, by its lack of Diesel exhaust, the world's first use of nuclear powered transport. And the same morning the Russians had announced plans to share fissionable materials and technical knowledge concerning nuclear power plants with Communist China and four European satellites. Although the occurrence of all these items on a single morning admittedly may not have been wholly coincidental, it did emphasize the imminence of large-scale nuclear applications and of coöperative efforts on a world, or at least half-world, basis.

It is well for us to recall what had led up to the events of this January morning, for its significance to man's future is far-reaching. During the preceding five years the number of atomic bombs in the possession of the United States, as well as their efficiency and range of utility, had increased continually. A natural result of this increase had been a corresponding increase in emphasis on other possible applications of our growing stock of fissionable material. It was clear that any large industrial application of atomic energy would involve more development than could effectively be carried on by secret government laboratories. As a result, private industries, and thus large numbers of additional individuals, would have to receive heretofore secret information, so that the nonmilitary phases of atomic developments could be pushed with full speed.

A definite impetus to this realization was supplied by the change in political atmosphere resulting from the incoming Republican administration in 1953. The Republican philosophy that as much as possible of national industrial development should be carried on by private industries led to a greater emphasis on participation by industry in the development of atomic power, not by means of government contracts, but as free agents. Much of the atomic research was already being carried on by industry, but as secret projects separated from its normal activities. This new emphasis moved also in the direction of giving out more information publicly, because secret information, gained under government contract, tends to remain unavailable. The influences just mentioned coincided to produce a move toward greater liberalization of information security, which began to have effect in the first year of the Republican administration.

After much discussion of the way in which industry could be brought into the picture and thus aid in the more rapid development of industrial atomic power, important amendments were made to the McMahon Act under which all atomic energy had been operating in the United States since World War II. The changes in the McMahon Act were primarily designed to make it possible for industry to participate in a free manner in the development of nuclear reactors that could produce economic power, and to make coöperative efforts with other nations possible. The important provisions of the modified Atomic Energy Act of 1954, signed by President Eisenhower on August 30, were as follows:

The purpose of the program was stated to be that "the development . . . shall be directed so as to promote world peace, improve the general welfare, increase the standard of living, and strengthen free competition in private enterprise." The Act made possible bilateral agreements with foreign nations, including allocation of fissionable and other special materials for construction of research and power reactors abroad, as well as exchange of classified and unclassified data. Under the Act the government could license fissionable fuel to private industry, retaining title to it, with the industry allowed to sell the electrical power. It also became possible for the Atomic Energy Commission to determine if access to classified information could be allowed with less than the previous full FBI investigation. By early November the Commission had set up a low or "L" clearance category for industrial data requiring only a brief "national agency check" for access. This procedure was simpler and much more rapid than the full "Q" clearance previously necessary for access to classified data.

It is important to realize the historical order of the events in 1953 and 1954, for the opening up of atomic energy to industry and to other nations at the Geneva atomic conference in August 1955 was not the result of the friendly attitude of the Soviets, as might be judged from an uncritical feeling that it had all happened because of the friendly "summit conference" of July 1955. Actually, as we have just seen, the initial opening up of industrial atomic energy to free enterprise came a full year before the public change in Soviet attitude and plans for the modifications in our policy had been started much earlier.

The modifications in the Atomic Energy Act, and shortly thereafter the liberalization of the official "Declassification Guide," which spells out the actual information that may be publicly released, both depended not only on the state of development of atomic energy in the United States but very critically on what our views were concerning the Soviet position in the field. The prevalent opinion shortly after the war was that the Soviets would not be able to eliminate our lead for many years, if they did not have access to our secret information. However, the activities of the Soviets themselves soon changed this view: within a few years it become evident by their actual accomplishment that they were able to make not only atomic bombs but H-bombs as well.

The realization that withholding of information would not stop the Soviets, but would certainly hold back our own effort, gave additional impetus to the adoption of the concept of security by achievement instead of mere concealment. According to this concept, we must advance our own program to attain real security, even if the procedure involves fewer secrecy restrictions. During the years 1953 and 1954, the combined effect of these various factors led almost inevitably to a transformation of the atomic-energy field from a closely guarded military activity to one in which international coöperation became not only important but desirable. It was clear that the Soviets could make atomic bombs. In doing so they probably had developed and built plants for the separation of U^{235} and U^{238} as well as nuclear reactors. Thus it was logical to assume that they were doing about the same things as we were in developing atomic energy for industrial power. This fact, together with the desire on the part of American industry to get into this new branch of engineering development and the need of many small nations for atomic power, much greater than that of the United States, accelerated the desire to get things into the open. This then was the setting for the proposal made by President Eisenhower at the UN in December of 1953 for world-wide coöperation in atomic energy, a situation very different from that existing when the UN had started its abortive discussions on international control of atomic energy almost ten years before.

President Eisenhower's "Atomic-Pool" Proposal

For all the reasons just discussed the situation was ripe for world coöperative effort in atomic energy on December 6, 1953, when President Eisenhower made his atomic-pool proposal in his speech at the United Nations. The conditions for attaining coöperation were not created by the President's speech, for things were moving definitely in that direction, but the speech did provide the immediate incentive that was needed to produce concrete results. At this time many of the small nations in Europe were trying to start programs in the field of peacetime atomic energy, primarily with a view to production of electrical power. In most of these countries fuel is scarce and expensive, and the power engineers in Europe, perhaps strengthened in their beliefs by lack of knowledge of many of the technical difficulties, were looking forward eagerly to atomic energy as the solution of their power problems. When Eisenhower's proposal was dramatically revealed to the world, these engineers turned immediately to the United States for a rapid solution of their problems. The serious power shortages in Europe as well as the potential advantages of atomic energy for these countries were obvious. The great hopes of the European engineers were equally obvious, as were the possibilities of great disappointment and reaction against the United States if concrete results were not to follow quickly from the President's proposal.

The latter unfavorable reaction materialized surprisingly soon, for during the months after the President's proposal, months during which no follow-up was apparent, the opinion was expressed with increasing frequency that his speech had been mere propaganda, with no attempt to implement it with concrete action. In actuality, of course, but unknown to the Europeans, this was a period during which the United States and Russia were trying to reach agreement on the way in which the atomic pool would be organized, but, as became public knowledge later, the Soviet insistence on elimination of bombs by simple agreement stood in the way of concrete results. After many months, however, when it became clear to our government that the Soviets would not go along with the Eisenhower plan, the United States went ahead with several types of international atomic coöperation with the Western countries alone.

In accordance with this program, in the autumn of 1954 the United States announced that it was making several concrete steps to advance world-wide beneficial application of atomic energy: scientists from other countries would be trained in reactor technology at a school (later set up at Argonne Laboratory near

Chicago); technical publications would be sent abroad to help other countries; and a sizable amount, 100 kilograms (220 pounds), of U^{235} would be made available for distribution abroad. It was also suggested that an international conference on peacetime atomic energy be held within one year. These developments, plus several others dealing with biological training, made possible by the amended Atomic Energy Act of 1954, were a concrete demonstration that the United States intentions announced by the President in December 1953 were not mere propaganda but were serious proposals for international coöperation. Most of these proposals originated with the new chairman of the AEC, Admiral Strauss, who had the enthusiastic support of the President.

As plans went ahead for the various steps of the United States plans during the winter of 1954, it was obvious that the suggested international meeting would be an event of first importance if all nations would participate fully. It was also clear that the Western world was looking forward with such eagerness to the realization of the benefits of atomic energy that the Soviets could hardly avoid joining the coöperative effort themselves.

The General Assembly endorsed the United States proposal for an international conference in December 1954. Things went somewhat slowly immediately thereafter; there was no rapid move made on the part of the AEC to declassify additional materials specifically for the conference, material that in the minds of many scientists was essential to progress in the field of peacetime atomic energy. However, as it became known during the winter that the European nations were eagerly looking forward to the meeting as a real break-through in secrecy in atomic affairs, efforts were speeded in the AEC to put through a declassification of fundamental reactor data in time for the Geneva meeting. Even though we had no intimation of the Soviet view of the conference, it was certain that the Western world was expecting the United States to reveal significant information for peacetime atomic-energy uses.

The scope of the international conference clarified during late 1954, and it became abundantly evident that it was destined to be something far larger and more important than anyone had visualized initially. It was as if each large country felt that it was obviously necessary to support such a worthwhile plan, and then, when all the smaller nations became so enthusiastic about it, they found themselves in a serious competition. Far from being in a mere propaganda show, they were competing with each other in a serious review of all phases of the peacetime uses of atomic energy.

Early in the conference planning, the United States Atomic Energy Commission had more or less turned over the conference to the United Nations, probably with the feeling that it was actually a matter of a trade fair, and properly something to be handled by our UN representatives. Before long, however, the AEC had put many of its best men on preparations for the conference, men who were to spend essentially all their waking hours for many months on arrangements for Geneva. What better indication need we have for the seriousness of the final AEC attitude than the decision and subsequent all-out effort that produced an actual working reactor for exhibit at Geneva, built in a few months in the United States and shipped to Geneva in time for the opening of the conference?

Even with the growing importance of the meeting, however, it was not at all clear early in 1955 whether it would be a serious discussion of beneficial applications of atomic energy or primarily an extensive means for spreading of propaganda. That the latter might be true seemed painfully probable in January 1955 when a special five-man planning committee, appointed by Secretary General Hammarskjold, met at the United Nations headquarters in New York. Here Skobeltzyn, the Soviet representative, started by advancing the oft-repeated and discouraging Soviet position that peacetime atomic energy could hardly be discussed unless all participants first agreed to ban atomic and hydrogen bombs. This, the standard Soviet position in all previous atomic discussions, momentarily threatened to bring the conference to a standstill when it had hardly started moving. And far from being a private presentation, the Russian position was described in detail by Skobeltzyn on a United Nations radio program during the same week that the meeting of the small planning group was actually in progress.

But in spite of the initial Soviet position, planning for the conference did proceed, and a schedule for submission of papers, their selection for oral presentation at Geneva, and printing of the proceedings did take shape. The success of the meeting was assured several months later, when, following the initial invitation of Mr.

Hammarskjold, over 1000 papers were submitted by the 73 nations that agreed to participate. The seriousness of the Soviet position with regard to the conference was apparent when a paper was submitted on the first Soviet atomic-energy power plant, one of 5000 kilowatts electrical capacity. Complete details of this plant were to be presented, whose very existence had been doubted by many.

The Geneva Atoms-for-Peace Conference

The months between the initial planning meeting in January and the actual conference in August were marked in the United States by an ever-increasing tempo in preparing papers for submission, hurrying through an extensive declassification of data for presentation, and building of elaborate exhibits for display in Geneva. As it became more and more clear with the passing months that the meeting would be of tremendous significance, correspondingly greater efforts were made to supply significant information. As the United States release of data was always prepared in consultation with the British and Canadian authorities, a conference of the three nations was held and rules were liberalized, just in time for the newly declassified material to be included in the papers submitted to the United Nations for the conference.

As the abstracts of the papers submitted to the Conference Office of the United Nations were translated and became generally available, it was obvious that all countries were attempting to present the best technical material they could in the fields to be covered at the conference. It was a great joy to learn that the Soviet abstracts contained none of the propaganda material that had appeared in the early planning meeting in January; the Soviet abstracts contained good, solid, technical material, with no boasting or political overtones. The coöperative attitude of the Soviets was clearly shown in June when they agreed to send all their nuclear cross-section data, destined for presentation at Geneva, to Brookhaven Laboratory, New York, so that the data could be compared with those from other countries and printed in time for distribution at the conference itself. These data appeared at Brookhaven a few weeks later, precisely on time, and as a result could be used very effectively in the actual discussions at Geneva.

The conference itself proved to be larger than anyone had envisaged. The opening session in the Palais des Nations, shown in Fig. 40, gives some impression of its scope. Of the papers submitted to the United Nations, about one-half were actually presented orally, with simultaneous interpretation into several languages. In addition to the papers, the 1400 delegates, plus an equal number of observers, could study the extensive exhibits of atomic-energy apparatus presented by various governments and by many industries. The outstanding exhibit, in the opinion of all who attended, I am sure, was the actual operating chain reaction, or the "swimming-pool reactor," built by the United States, shown in Fig. 41. Surrounding the pool of water serving as a radiation shield, the public could gaze on the blue glow signifying the release of atomic energy in a completely controlled, harmless manner. After being viewed by thousands during the two weeks of the conference, the reactor was formally turned over to the Swiss, who have installed it at Zurich, to be used for research and training.

The wealth of technical material presented on the many beneficial aspects of atomic energy is just what we have been considering at some length throughout this book; hence we do not need to emphasize the broad range of subjects discussed, from tracers to millions of kilowatts. The important matter for our attention at the moment is that a great flood of material was released that had been held back before, material that was discussed freely at Geneva, without political implications. It was certain that each of the large countries was pursuing the military aspects of atomic energy and hence was holding back information in certain categories. But it was amazing how few embarrassing situations occurred as the discussions would move near the boundary line separating secret from open data.

There was general agreement that on the technical level the United States was leading the world and, correspondingly, had presented the largest amount of technical information at the meeting. From a narrow point of view one might conclude that we lost ground at Geneva because other countries learned much more from us than we from them. However, the great gain to the United States is not from the technical material we received (and we did gather much material of value) but from the accomplishment of the

Fig. 40. A general view of the opening session of the Atoms-for-Peace conference in Geneva, August 1955. (Courtesy of Magnum Photos.)

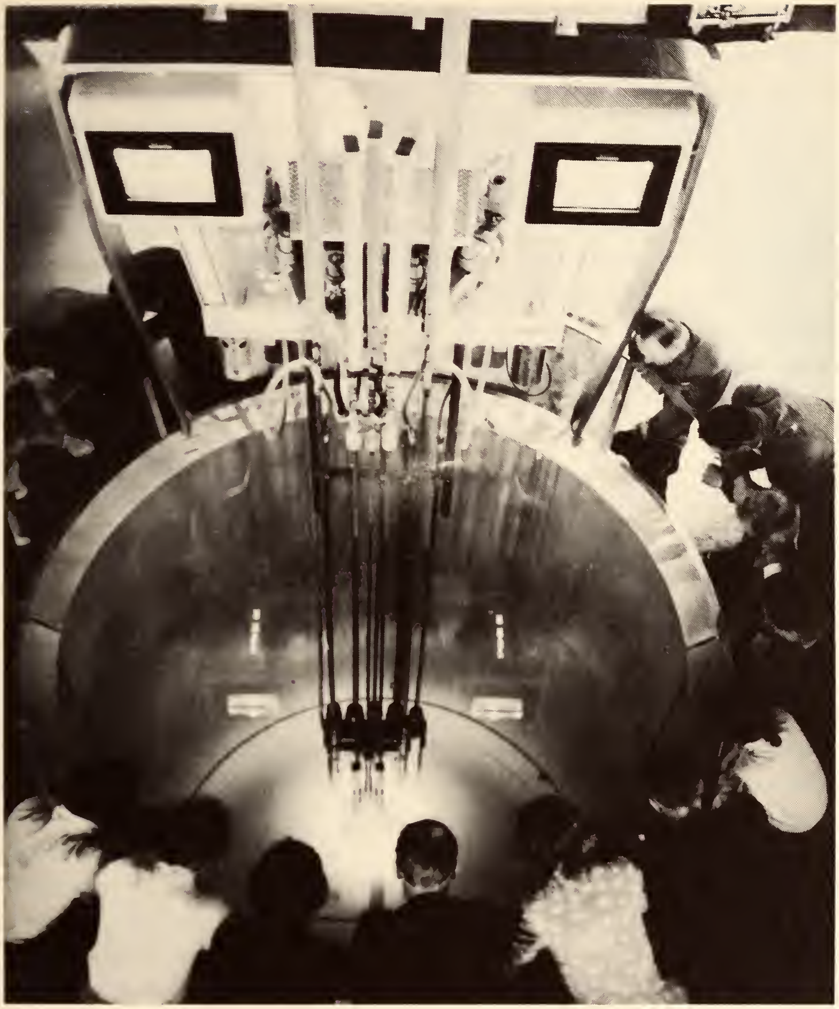


Fig. 41. The "swimming-pool" reactor built at Geneva by the United States. The reactor is now in operation at Zurich, Switzerland. (Courtesy of Union Carbide Corporation.)

broad, altruistic aspects of the original Eisenhower proposal, from the overwhelming evidence presented to the world that we are serious about atomic Marshall aid, that we have already begun sharing with the world the gains of the new nuclear age. The hundreds of papers presented by American scientists, jammed with information on raw materials, electric power production, basic nuclear data, and applications to biology, agriculture, and medicine, were obviously no empty gesture but a great outpouring of help to the entire world.

Another, and perhaps in the long run the greatest, positive result of the Geneva conference was the successful coöperation of Eastern and Western scientists, first, as a resounding demonstration that a certain segment of the population can work together successfully, and second, because the strong personal bonds set up among these men, if continued and strengthened with time, may exert a significant effect on the Soviet government in the direction of peaceful coexistence.

The first effect can be said to be operating already, for in the United Nations discussions on disarmament in the autumn of 1955 the proposed inspection system was described by Ambassador Lodge as something that might work in a manner analogous to that of the International Atomic Energy Agency and help create mutual trust. Here we see international coöperation in atomic energy almost taken for granted and already serving as an example for similar action in other spheres. Another possible analogous coöperative effort is the international study of the effects of radioactive fall-out following nuclear-bomb tests, which was proposed to the United Nations by the United States in the summer of 1955, and is now well under way. Although this coöperative effort is on the technical level, it will merge in the disarmament field because of possible regulatory decisions concerning bomb tests. Success in this venture would be a definite step of value toward mutual understanding.

The second possible beneficial result of the personal relations established at Geneva—the influence of the Soviet scientists on foreign policy—is related to the question of their position in Soviet life. In this respect it was abundantly clear to all of us who met them at Geneva that the Russian scientists were well-treated, almost pampered, members of Soviet society. The informal conversations that became more and more frequent as the days passed, and initial awkwardness disappeared, revealed that they were surprisingly frank about their likes and dislikes, apparently having no fear of reprisals, reasonably free to pick the subjects of research that interested them, certainly well paid, and completely relaxed about their future.

The discussions we held with them, aside from the language difficulty (which rapidly decreased as more and more of them began to use the English that all seem to have studied thoroughly), might well have been those at any American technical-society meeting. Our workers discussed their difficulties as well as their successes with their Eastern counterparts and received the same frankness in return. The mutual respect developed in this atmosphere had a firm foundation and the obviously important position of the Soviet scientists in their society makes it extremely likely that their respect for us will bear some good fruit. It may not be a bountiful harvest, but it is certainly a definite step forward. The Soviets' respect for Western science and scientists was great and unconcealed; they were familiar with us as individuals because of our published work. This was somewhat disconcerting, for their names were not known to us, their work having been unpublished before Geneva. They made no secret of the fact that many of our books, translated into Russian, were their standard references. On two separate occasions, for example, I was presented with translated copies of a book of mine on neutron research, as spontaneous gestures of friendship by Russian physicists.

At the conclusion of the present chapter we shall indicate how some of the contacts established at Geneva are already being expanded, thus supplying a basis for cautious optimism concerning the continuation of beneficial East-West communication in science. But first, let us look into the present standing of several representative countries, to examine the reality of atomic progress on the international scale and to judge if the optimism of Geneva concerning atomic plenty is justified.

Progress Since Geneva

The removal of secrecy restrictions with regard to the bulk of peacetime atomic energy that occurred in connection with the Geneva meeting has the result that progress since that time has been widely reported and requires no penetration of secrecy barriers to follow it. The release of information has actually done much more than make it easy to keep in touch with atomic-energy progress, for it has greatly accelerated the programs in almost all countries. The stimulus of the release of information has been particularly great in the small countries that could otherwise hardly have started an atomic-energy program. Actually, activities are enlarging so rapidly throughout the world that the released information becomes almost an embarrassment of riches. It is now somewhat difficult to keep in touch with the rapid progress, not because of secrecy but of wide expansion. The difficulty is accentuated by the fact that information released by each country is likely to be presented in such a way as to describe its particular program in the most glowing terms. Thus it becomes essentially impossible for the layman, even with much reading, to decide correctly "who's ahead" in the entire business. Because of the complexity of an atomic-energy program, almost any country can pick some phase in which she is concentrating and doing pioneer work, and hence can claim to be "ahead" of the rest of the world.

In order to decrease the confusion somewhat, it is perhaps a good idea for us to look briefly at the program of work in a few selected countries, to try to penetrate the publicity and evaluate with reasonable fairness the state of the atomic-energy art in these countries. We shall see that the comparison is not a straightforward quantitative matter, for the program in a given country must be judged relative to its peculiar needs, which may be unique to it and decisive in fixing the nature of an atomic program. Most of the emphasis at the Geneva meeting, particularly in the comparison of one country with another, had to do with atomic power; we shall also concentrate our attention on this important aspect in considering the comparative programs throughout the world. We do not need to spend time in describing the power program in the United States, for that was dealt with rather completely in Chapter 4. We shall come back to it, however, in order to relate it to progress in other countries after we have examined the highlights of their programs.

Let us look then at the progress in a number of countries now that some two years have passed since Geneva and the results of the conference are becoming evident. It is impossible to cover the activities in even a few countries in a complete manner; even to list the major projects would probably not be instructive and certainly dull. Rather we shall look only at the atomic highlights of those countries that are the major actors in the atomic-energy drama, and then at a selected few of the smaller countries in order to illustrate their specific functions and problems. The selection will be somewhat on a personal basis, for it seems desirable to base the description as much as possible on the firsthand experience I have had with the atomic-energy work in these countries rather than the reading of reports about it. On a number of visits to Europe since 1949 I have had excellent opportunities to learn directly about the work in most of the countries, by visits to laboratories and discussions with scientists.

During and immediately after the academic year 1953–54, which I spent mainly as a Fulbright professor at Oxford and Cambridge, I was able to devote a total of almost six months consulting and lecturing at European atomic-energy laboratories, in England and on the Continent, from Oslo down to Rome. On other trips, both before and after this year's stay, I was able to follow closely the way in which atomic facilities were coming into being in a number of countries. The close contacts with so many scientists gave me a good picture of the atomic situation in Europe about 1954, with vivid impressions of their hopes for the future and their feelings toward America and Russia. Contacts with these scientists were renewed at Geneva, and in addition I learned of the Soviet work, directly from their scientists, for the first time. Several visits to the European laboratories since Geneva have helped greatly so that I am able to report at firsthand on their present status. The progress, problems, and aspirations of the countries I happen to know best are typical of all, however, and we shall have covered the essential facts, applicable to a large extent to all, by means of several, for which my personal knowledge is greatest.

Measured in dollars, the magnitude of the combined effort of all Western Europe is much smaller than that of the United States. In spite of the limitation in size, however, the programs are extremely vigorous, and in some countries are being rapidly pushed ahead to practical application, in some respects much faster than our own. As we have already warned, however, this does not necessarily mean that someone is "ahead" of us. Each country's progress must be judged relative to its own needs, as we shall see, and it is thus extremely difficult to rate programs on an absolute scale.

It is noteworthy in this connection that most of the European atomic-energy work, particularly in the smaller countries, had no secrecy restrictions at all from the very beginning. This situation provided a marked contrast to the United States where much research on atomic-power production was still classified until the extensive declassification for the Geneva conference.

Great Britain. In trying to select a single outstanding general impression characteristic of the European effort before Geneva, I am always reminded of a point of view expressed to me forcibly by Professor F. E. Simon, of Oxford University, late in 1953. It was an opinion later reinforced many times by scientists from other countries as well. Greatly impressed by the magnitude of a complete atomic-energy program, he felt that it could very well prove to be more than any single European country could manage economically. He was considering all the complexities of the production of uranium metal and of heavy water, chemical separation of plutonium, enrichment of uranium by gaseous diffusion, bomb development, and the basic research on which all of these depend. The prospect of building a complete atomic-energy industry involving all these elements, in a country still recovering from war's depletion of non-atomic industries, is truly one that could well make one pause.

In the light of the magnitude of the prospect, it seems logical to conclude that a single European country should not try to go it alone. It would seem better to coöperate with other European countries or depend on the United States for solution of some of the problems. In the time since 1953, however, and especially since Geneva, it has resulted that a compromise position has developed, merging the advantages of the several approaches. The various components have differed from country to country as development continued. The continental countries are working together at Euratom, as we shall see; much help has been obtained from the United States in certain countries, and England to a large extent is going it alone. In spite of the legitimate fear expressed by Simon, it is certainly desirable, if possible, for Britain to develop all phases of atomic energy, from tracers to bombs. The fundamental reason for the British decision was not merely the lack of exchange of information on industrial applications of atomic energy that led to a feeling of "we'll go it alone." In addition, and of greater weight actually, was a definite feeling that the only way to develop a sound and substantial atomic-energy industry was for the British to become experts in all its phases. It is difficult to decide, of course, to what extent national pride contributed to this conclusion, but all things considered, and correcting somewhat for this last effect, it certainly is the logical basis for the British effort. And the British program is eminently well designed to cover all phases of the atomic-energy field, yet in a planned, orderly way, so that, while practical results will be felt as soon as possible, the over-all mastery of the field will proceed simultaneously, albeit slowly.

In examining the various phases of the British atomic effort, whether by reports of discussions in Parliament or firsthand from engineers, it is clear that the program is orderly, well-integrated, and one that will give useful results quickly, not only in military applications but in production of electric power. An over-all order exists that is a bit surprising when compared with the many rival reactor projects in the United States, the varying fortunes of different reactors as time passes, the Congressional discussion of matters at times highly technical, with all the attendant publicity, the controversy over the correct role of industrial participation, and the ever-present concern for security of secrets. This difference between British and American atomic programs is real, but there are basic reasons for it, not merely the British talent for orderly management and the present civil-service status of most of the workers. The well-integrated nature of the entire program relative to that of the United States arises partly from its smaller size and from the high degree of nationalization of industry. By far the most important reason, however, is its clear-cut goal—forced by the power hunger of Britain. The need to replace the dwindling coal supply with some other power source will become so acute that it can confidently be said that Britain simply could not get along without atomic-power production by the turn of the century. Importation of coal has now begun, in spite of great efforts to increase domestic production, and prospects are that the importation will increase. While it is not true yet that coal is being carried to Newcastle, it is, at least, to England.

The present status of the program illustrates well the British emphasis on power as soon as possible. Two Hanford-type (although air-cooled) plutonium production reactors are in operation at Windscale, building up a stock of fissionable material for bombs or for power-breeders. The first power-producing reactor started operation in 1956 at nearby Calder Hall (Fig. 42); it is not of advanced design, but something that works *now* and extremely well. Instead of high-pressure water, liquid metals, or highly enriched fuels, we have here a simple graphite-moderated, natural-uranium reactor. Its only radical "new" feature is compressed-gas (CO_2) cooling, although this method (with nitrogen as coolant) had been in use at the French P2 reactor at Saclay for a year before. Such a simple reactor would hardly be considered seriously as a power reactor in the United States because of various inherent uneconomical factors. Nevertheless, two of these "old-fashioned" reactors are now operating at Calder Hall, producing about 80,000 kilowatts of electricity, thus replacing the consumption of about 400,000 tons of coal per year, and several more are under construction.

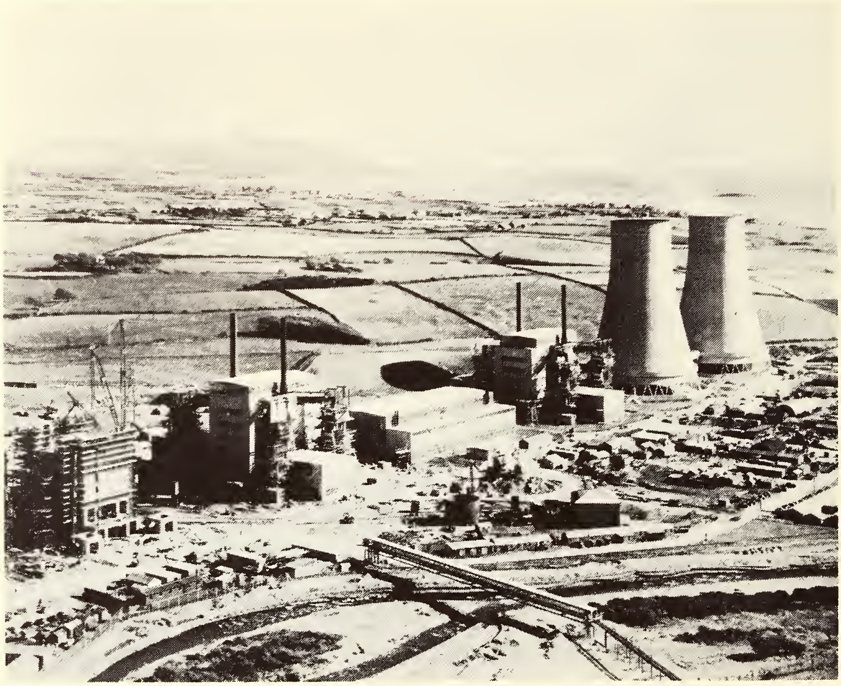


Fig. 42. The first British atomic-power plant at Calder Hall. (Courtesy of British Information Service.)

At the same time the more remote phases of the program are proceeding. In 1954, "Zephyr," a zero-energy fast-neutron breeder, was operated for the first time, using plutonium from Windscale as fuel, and a 10,000-kilowatt fast-neutron power plant is now being built in Scotland. The depleted uranium resulting from the Windscale operations is not forgotten in the national picture, but goes to Capenhurst for enrichment by gaseous diffusion and is then converted to fuel for the Windscale reactors again. In addition, design studies have begun on a pressurized light-water power reactor. The emphasis on power as soon as possible, with less emphasis on economy than in the United States and a longer-term view toward the most efficient integrated schemes, is abundantly evident in these interlocking activities.

The predominant position of power production at stationary plants as a goal in the British program is obvious and it helps to give the entire activity a definite cohesion. There is no combination of goals, as in the United States, where mobile power, in the form of propulsive units, competes in the budget with stationary power producers. The present practical result is that the British have plants now turning out reasonably large amounts of electric power, whereas the United States has essentially none as yet. The abundance of natural power sources in the United States also removes the sense of urgency. The result of course follows that there is a reluctance to build a particular power reactor until lengthy investigations have proved it to be the best possible.

The British view of their fuel situation, and its relation to atomic-power production is well illustrated by the debates in Parliament arising in connection with atomic-energy legislation in 1953. For example, Lord Falmouth criticized the government program in the House of Lords, stating that the plan to build a 50,000-kw power station (Calder Hall) at a cost of £6 million should be replaced by a "less grandiose scheme." This accusation of extravagance is somewhat surprising, when we compare this $17 million with the $85 million for the United States power plant at Shippingport. Lord Salisbury, who as Lord President of the Council is responsible for the British atomic-energy corporation, answered with a detailed account of the reasoning behind the program. He explained that production of electric power, a vital matter to Britain and of great importance in the atomic program, should not be under control of the Minister of Supply as it had been, and hence was placed in the new statutory corporation, of the type that had controlled production of coal, electricity, and gas. The purely military aspects of atomic energy, that is, design and production of bombs, he explained, are not a direct concern of the corporation and were to remain an activity of the Ministry of Supply.

The optimism of Lord Salisbury concerning the future of atomic power in Britain is illustrated by his prediction that "with the program under examination realized, most of the country's electricity would be generated from atomic power by the year 2000." Lord Cherwell, who as Churchill's adviser was until recently responsible for the program, and Professor Simon, men who understood full well the problems that must be solved before this happy state of affairs is realized, do not share this extreme optimism. Both, however, agree that atomic production of electricity is essential for Britain and that the strongest possible effort, which necessarily implies careful concentration of limited resources, is justified.

Their plans for the next few years underline the British determination to push ahead with electric-power production. Encouraged by the successful operation of the Calder Hall plant, the British announced early in 1957 an increase in the tempo of the development of atomic electric power, in order to attain a goal of 4 million kilowatts installed capacity by 1965, just twice the estimate made in 1955. That amount of power would require about 13 million tons of coal per year by present methods, some 6 percent of the total coal production in Britain today.

France. As we are more or less familiar with the well-publicized fuel shortage in Britain, the emphasis on power production in the atomic program there is easily accepted. However, not nearly as much seems to be known about the French fuel situation. In my own discussions with the scientists at Saclay, the French atomic-energy laboratory near Paris, I was surprised to learn that, in their opinion, atomically produced electricity was even more urgent for them than for the British. The French electric power load, about 4 million kilowatts, is now supplied about equally from poor coal and water power, with little chance of increasing either substantially. Power from tides has actually been given serious consideration but would not result in large increases in available power, and would be expensive and of uncertain long-term reliability.

Atomic research now centers around P2, the heavy-water-moderated reactor at Saclay that possesses a particularly high intensity of neutrons, and is thus an extremely valuable machine for research. As already mentioned, this reactor has been successfully cooled by compressed gas (nitrogen at first, but later carbon dioxide), the system also used in the British power reactor at Calder Hall. A 40,000-kilowatt (heat) plutonium-production reactor is operating at Marcoule, on the Rhone River. It is air-cooled and produces some electric power, but not enough to supply the needs of the reactor itself. A large amount of power is required for operating the fans for cooling the reactor, actually somewhat more than is produced. Two more reactors, carbon dioxide cooled, are now being built at Marcoule also, and these will supply about 40,000 kilowatts of electric power.

Other European Countries. Norway got a very early start in the nuclear-power field, helped greatly because she possesses a very important heavy-water plant. Norway instituted a coöperative plan with the Dutch, who had uranium, and the combination has worked very effectively. The research reactor, JEEP (Joint Establishment Experimental Pile), near Oslo was built very quickly, starting operation in 1952, and has continued with little difficulty, at a power level of about 300 kilowatts. A very active research group has been formed at this reactor, one that exhibits particularly well the present coöperation among European nuclear scientists. In addition to the workers from Holland who shared in the construction of the reactor, I remember talking to scientists from France, Yugoslavia, and India, all of whom were working at the reactor during a visit I made to Oslo in 1954. The results obtained with the research reactor are being utilized in plans that are now going ahead in Norway for the next reactor, possibly one to produce large quantities of low-pressure steam for use in the wood-pulp industry. There is in addition active planning for a mobile reactor for ship propulsion.

The Swedish research reactor, unofficially called SLEEP (Swedish Low Energy Experimental Pile), has been in operation since 1954. While it is of a rather conventional design, using heavy water as a moderator and natural uranium fuel, its surroundings are unique, as it is located in a large room blasted out of rock under a park in Stockholm. This method of construction does not imply that the Swedes considered the reactor an extreme hazard; actually it is a relatively common procedure in Sweden. This reactor is being used primarily to gain experience in neutron physics. At the same time detailed planning is going ahead for the second Swedish reactor, an actual power producer to be built a few miles from Stockholm.

In Holland an extremely active group of scientists and engineers, having gained knowledge from the coöperative construction of the Norwegian reactor, are pushing ahead on plans for a power-producing reactor. A high-intensity experimental reactor being purchased from the United States will supply neutrons for tests necessary in the power-reactor design. In addition, at their research center at Arnhem the Dutch engineers are considering reactor designs much more advanced than any discussed in the United States. Because of their experience in handling slurries and powders, they are anxious to apply some of the techniques involved as means of transporting the uranium fuel through a reactor. These techniques, to put it mildly, are unusual, such as "fluidizing" powder by blowing gas through it. However, if successful, they will avoid all the complicated problems of protective coatings and removal of fuel elements that apply to the usual solid-fuel reactors. This trial of completely new techniques in nuclear power is an extremely healthy influence, in spite of the limited experience that the Dutch have had with high-power reactors. Sometimes completely new developments of great importance come from just such small groups, free to try radical approaches because they are not committed to large and usually conventional reactor projects.

In the other European countries atomic-energy programs are not as far along as in the ones we have considered. Nevertheless, in every country, groups of varying size, but of unvarying optimism and enthusiasm, are hard at work, each considering atomic energy as an indispensable part of their industrial future. The individual efforts are tiny compared to that of the United States but because of that very fact it is possible to try new ideas in a way that can hardly happen in this country. For example, a small group working under Heisenberg in Göttingen is making graphite, on an experimental scale, of a density much higher than is found in our reactors. The German scientists also feel that they can develop economical methods for making heavy water; one certainly gets the impression that their chances of success are very good. The Italians and the French are also working on heavy-water production; perhaps the Norwegian monopoly in Europe will not be long-lived.

Finland is a particularly interesting case, being in a position where she is strongly influenced by both the East and the West. The nuclear-energy program now envisaged by the Finnish Contemporary Energy Committee (corresponding to the United States AEC) shows no inclination to start planning immediately for a power reactor. The members seem reluctant to commit themselves to any definite line of power development, much less start any actual construction. The reason for this hesitation is not any plethora of water power, for, extensive as moving water may be, all of the desirable sites have been developed already. On the other hand, the Finns would be interested in getting, as soon as possible, a reactor producing process steam for their tremendous wood-pulp industry—if the cost would be low. But they have little interest in a high-power reactor for electricity in the next few years, feeling that improvements are inevitable and that they would do better to let the large countries do the development.

An important element in the Finnish position is their fear that, if they cannot manage a complete program on their own, they will become subject to the control of one of the large nations, on whom they would then depend. It is easy to understand their reservations when one realizes, for example, that their entire supply of oil today comes from the East and can be cut off at any instant if the Soviets so desire. But most American observers feel that too much caution now might hold back the future development of a Finnish atomic program. Two vital steps that Finland could take at the present time are construction of one or more research reactors and the training of key people abroad.

Soviet Union. At the time of the Geneva Meeting there was, of course, intense interest in the material that was presented by the Soviets. The abstracts that their scientists had submitted indicated that they intended to present solid technical information, not propaganda, and furthermore that they had already made real accomplishments in the production of atomic power. The paper scheduled for presentation on the 5000-kilowatt atomic-power station aroused great speculation, with some predictions that this paper would be propaganda and that the power station did not really exist. However, the paper itself was a typical open scientific report giving a tremendous amount of detailed information about the atomic-power plant, including photographs of the reactor and the electrical generating equipment. Thus there was no doubt at all about the existence of the plant, which, according to the Soviets (and it seemed reasonable to the listeners), has been in operation since 1954. The reactor building itself is shown in Fig. 43; when we asked the scientists about the somewhat dated style of the building, they replied "Well, you know what architects are like—they wanted it that way!" Actually—and one would hardly have thought it possible at the time—American scientists saw this generating station in operation when they visited Russia less than a year after the Geneva meeting. The great number of other papers presented by the Soviets showed that they had not only had an atomic-power station in operation, but that they had large plants for separating isotopes,

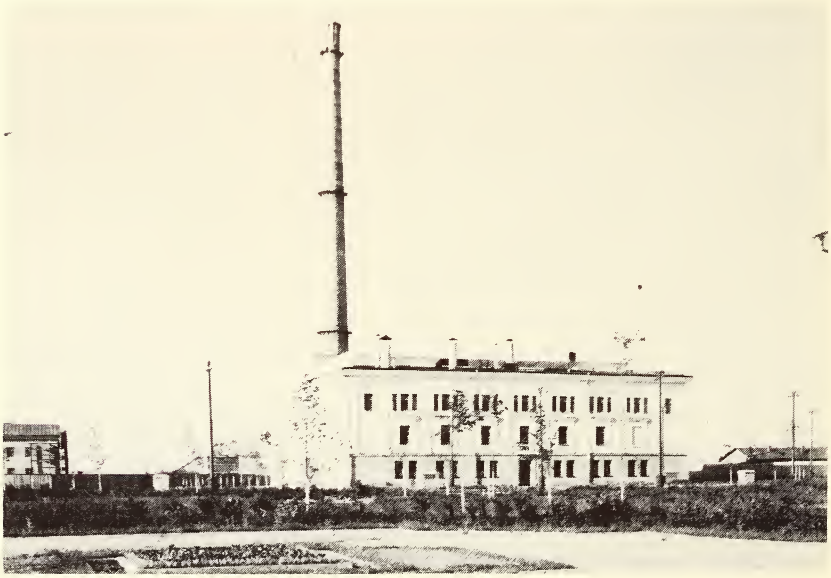


Fig. 43. The building in which is housed the Russian power plant, which has been in operation since 1954, generating 5000 kilowatts of electricity. (Courtesy of I. I. Novikov, Moscow, U.S.S.R.)

several research reactors that were about equal to those in the United States, and all the auxiliary equipment to go with these large reactors.

In connection with the Russian power plant we have a good example of the difficulty of specifying the relative standing of various nations in the atomic-energy competition. The bare facts that the Russians had a plant generating 5000 kilowatts of electricity in operation since 1954 would make it seem that they were much ahead of all other nations in the world who had no such power stations in existence. However, a more meaningful view of the relative status must involve not only the mere dates of start-up, but the precise nature of the reactors that are involved. The Soviet power station, for example, is a type of reactor that would be considered somewhat out of date in the United States, for it is built with graphite as a moderator and is cooled with water, the uranium fuel being only slightly enriched in the U^{235} isotope above normal uranium. This type of reactor would not be considered a serious competitor in the power-production field in the United States and we would hardly consider building one in this country. It is essentially the same as the Hanford plutonium-production reactors, built in 1943, which, as we saw in Chapter 4, would not be efficient power-producers. As we have described in some detail in Chapter 4, the program in the United States is one in which many types of reactor are investigated, and in great detail, but only a few of the most hopeful are considered for actual construction. This process means that *no* reactor is likely to be built until detailed development, not only of that one but of many competitors, has proceeded to the details of all phases of its operation.

The Soviet program actually resembles that of Britain more closely than that of the United States for, as we have just seen, a type of reactor somewhat similar to the Russian has been built at Calder Hall. Whereas in Britain the reason for building a reactor quickly, even though of a rather old-fashioned type, is shortage of fuel, it is not clear whether the Soviet power station was built at an early date because of a real power shortage, or simply from a desire to have the world's first atomic-power station built in Russia. Of course the correct type of program in the atomic-power field differs from country to country, and even within a single country it is not easy to decide on the exact program that should be followed, in the light of the many variables involved. Even in the United States, where sufficient money is available to build many types of reactor, there is still a large amount of controversy about the correct construction schedule, as we shall see in the next chapter.

In addition to constructing their first power reactor, which is of somewhat low capacity and rather inefficient, the Soviets are moving ahead rapidly with other types of reactor as well. Some rather detailed reports were given at Geneva which indicated that they are definitely developing a fast-neutron reactor, which, as we have seen in Chapter 4, has a very good chance of successful breeding. Various other types are also being designed, involving such features as heavy-water moderation, gas cooling, homogeneous cores, and boiling water, thus representing practically all the types being considered in the United States. When the Soviets presented their work at Geneva on their operating power reactor it was pointed out by American scientists that the *conversion ratio* (amount of plutonium produced relative to uranium consumed, as discussed in Chapter 4) for the reactor is extremely small, actually much less than the conversion ratios in the types of power reactor being considered in the United States. Although it seemed clear that the Russian scientists were very much impressed by the conversion ratios quoted for the reactors being designed in the United States, they of course instantly pointed out that *their* reactor was actually operating, and that they too intended to get higher conversion ratios in reactors still on the drawing boards.

It is very doubtful whether many additional reactors in the Russian power program will be of the same type as their first operating power reactor; rather, it is almost certain that their next reactors will be of the advanced type similar to those now being built in the United States. Since the Geneva meeting additional information concerning Soviet plans has been gained from a detailed talk given by Kurchatov, one of their engineers, at Harwell, the British laboratory, in April 1956. He explained that the Soviets plan to have about 500,000 kilowatts of electric power being produced from atomic energy by 1960, involving the construction of three distinct types of reactor. These reactors are all to be built in the plains area of European Russia where fuel is scarce, rather than in Siberia, where cheap hydroelectric power is plentiful. In the autumn of 1956, however, a Soviet announcement described an expansion of these plans to the greatly increased estimate of 2 million kilowatts in the same year, 1960. Incidentally, this represents some two or three times the planned atomic-power capacity in Britain or in the United States (about 1 million kilowatts each) at about the same time, 1960–61. This goal is an extremely ambitious one when one considers the number of years involved between the first design and the final construction of such a large and complex industrial plant as a modern nuclear reactor.

The size of the program definitely establishes that the Soviets are putting a major effort into the successful attainment of peacetime atomic power. The talents of many scientists are clearly being devoted to this end; at Geneva it was abundantly clear to us that a very large fraction of the Russian program, even of the most basic nature, had as its ultimate goal the attainment of a successful power-reactor program. Thus the scientists who were measuring neutron cross sections, for instance, were obviously concentrating their work on those nuclei that would be important to the power program rather than those of great importance to basic physics only. There seems to be a distinct difference in this respect between the attitude of the Soviet scientists and those of the United States. The latter, even though attending an atoms-for-peace conference, were obviously interested much more than were the Soviets in the relation of their results to basic nuclear theory. Unfortunately, we cannot here enter the complicated question of which side will win out in this kind of basic research plus application competition. One important point that can be made, however, is that immediate devotion to practical ends will attain the short-term result probably more quickly, but at the same time will weaken a country as far as the obtaining of the basic information is concerned, the information that will be of great practical value a number of years ahead.

Comparative Position of the United States

Although we have already described in some detail the course being followed in the United States for the practical attainment of atomic power, it is well to compare some phases of the program with the parallel developments in other countries. In Chapter 4 we saw that, because ordinary fuels are abundant in the United States, the direction of our program has been more toward very advanced reactors, those reactors that can compete with the ordinary "fossil fuels," coal, gas, and oil, in the United States, where those fuels are relatively cheap. Because of the necessity of this competition, there is very little point in investigating or building reactors that can be shown in advance to involve a higher cost for electric power than now results from the ordinary fuels. This situation is the reason why in the United States essentially no effort has gone into the design or building of reactors involving graphite as a moderator with natural or slightly enriched uranium as fuel. These reactors, as we have just seen, have been built in the United Kingdom and in Russia. However, because of their small conversion ratio (low plutonium production), and the poor efficiency for transformation of heat energy into electricity that results from the low operating temperature, these reactors have not been considered as front runners in the United States.

An inevitable corollary of the advanced nature of the reactors being considered in the United States is the much slower time scale for their construction. It obviously takes many more years to design and build a reactor that will be a successful breeder than one using ordinary uranium and natural graphite, with its extremely low conversion ratio. The latter type will certainly operate, and in a most predictable way, and furthermore will generate a lot of electricity, but also it will use up much valuable U^{235} in the process, and as a result cost much more money than a successful breeder.

There is, of course, a real danger of going to an extreme in the desire for a reactor of efficient, economical operation; this extreme would be the situation in which *no* reactors were built because of the possibility that if we waited a bit longer we might be able to design an even better reactor. It is true that the United States program of building reactors would have produced practical results more quickly if we did not have this goal, of high-efficiency breeding at low cost, always in view. In fact, it is felt by some that if the United States program had been one in which we went ahead and built reactors, regardless of cost and efficiency, we might progress faster in the long run. This sort of argument, however, involves a lot of second guessing and it is not at all certain whether the program we are now engaged in is the best or whether there is a sound basis for criticism. It is of course true that neither the extreme of building whatever we can build, nor one of waiting an interminable period so that we have the best reactor, is sensible; the correct program must obviously be somewhere between these unwise limits.

Thus when we see the somewhat shocking news report that Britain has now an operating power plant and leads the world because she is producing more thousands of kilowatts than any other country, or that the Russians have had a 5000-kilowatt plant in operation since 1954, we must go to neither extreme in reacting to it. It is *not* true that the United States is behind these other countries because we do not have *x* thousand kilowatts being produced at the present time. On the other hand, it is no more true that the accomplishments of these other countries are negligible because we are interested in more advanced types of reactor. The success of an atomic-energy program must always be measured relative to the needs of the particular country in which it is being carried out. Certainly the program of Britain is eminently sensible for her own needs; likewise it is obviously *not* the program that should be followed in the United States.

It might be possible to compare by one method, on a reasonably absolute scale, the progress in various countries in power-plant development. This comparison could be based on the competition for the market represented by those countries interested in buying reactors. This is hardly a busy market place at present but it seems certain to quicken in the near future. In this connection, we could say that the country that leads her competitors is the one that will produce in a few years the most efficient reactor for general use in many countries. The way in which this accomplishment could be measured would be to see in several years time which reactors are being bought by countries throughout the world for their own needs. However, we are not quite at the stage where reactors are being sold on the open market—although we are getting close to this position, to judge by the vigorous promotion carried on by the atomic-energy industrial firms at Geneva! We must wait somewhat longer for application of this method of determining the country that is ahead in the atomic-energy race.

In the meantime it is extremely fortunate that coöperation on the international level is going so well that countries can help each other, even though their goals may not be exactly the same. The way in which this material aid has spread beyond national boundaries since Geneva is an encouraging story for international coöperation in general, and may well serve as a stimulating example for similar activities in other fields. So let us conclude our story of the international atom with an account of the international organization for atomic-energy coöperation, which has finally been realized after several years of planning, following President Eisenhower's initial proposal, based on the suggestion of AEC Chairman Strauss.

The International Atomic Energy Agency

Although things had moved rather slowly in the field of international atomic energy in the period immediately after Eisenhower's proposal at the United Nations in December 1953, about a year later it was clear that the demand for international effort was so great that some form of organization was almost inevitable. The General Assembly of the United Nations, on December 4, 1954, about the time that the Geneva atomic meeting seemed certain to occur, gave its unanimous approval to a resolution calling for the creation of an international agency for the peaceful uses of atomic energy. Although the Soviet members had tried to place the agency under control of the Security Council, only to have this move vetoed, they voted in support of the agency resolution.

On November 15, shortly before the unanimous approval of the General Assembly, the United States delegate, Henry Cabot Lodge, had announced that the United States had allocated 220 pounds of U^{235} for use by other countries. The next day the British delegation added to the amount by offering to contribute 44 pounds to the international agency. The announcement made by Lodge was one of various steps taken by the United States to show that she was willing to go ahead on the international level even if the Soviets should not participate. For example, in his speech at the opening of the General Assembly on September 24, 1954, Secretary Dulles outlined a series of steps that the United States was contemplating, such as the calling of an international conference, the opening of a reactor training school, and the invitation to a number of cancer experts to visit the United States.

Thus, even before the Geneva meeting had been planned in detail, the principle of an international agency had already been approved. In addition, the various offers made by the United States showed clearly that, even if the international organization did not come into being in a reasonable time, coöperation among nations would take place on a bilateral basis. Events moved somewhat more rapidly after the approval by the Assembly; in April 1955 it was announced that the United States had prepared a draft constitution for the international agency and had sent it to seven countries for their reactions. The independent steps by the United States also continued; in a speech on June 11, 1955 President Eisenhower offered research reactors and fuel to other countries, with the United States paying half of the cost. In the summer of 1955 the amount of material already made available the previous autumn to the international agency by the United States was doubled; by that time bilateral arrangements with a number of nations had been formulated also.

After the highly successful Geneva Atoms for Peace meeting in August 1955, progress continued on the formation of the international agency. A group of eight nations presented a statute for the agency to the UN General Assembly early in October. This draft statute was well received, and later in the same month the General Assembly unanimously approved a compromise form of this statute, containing only minor changes. The actual formulation of the detailed structure of the agency began when a twelve-member drafting committee started work in February 1956 in Washington. The drafting committee was able to finish its work expeditiously and on April 18 reached unanimous agreement on the text. The nations whose representatives performed this significant task are the United States, the Soviet Union, Britain, France, Canada, Australia, Belgium, Brazil, Czechoslovakia, India, Portugal, and South Africa.

The plan for the agency was submitted to a conference of 82 potential members of the international organization at a special conference in the autumn of 1956 held at the United Nations in New York. The 82 nations began their conference on September 20 and after a month's discussion, most of it on a high level and with little acrimonious debate, completed the agency plan, soon reached agreement, and signed the final statute on October 23. The actual existence of the agency, however, must await the ratification of the statute by eighteen governments. The functions of the agency, officially the International Atomic Energy Agency, were not specified in full detail, but provisions were made so that it could act as a banker to hold fissionable materials that could be made available to the various member nations. It also could aid in setting up atomic plants and in supervising safety rules for reactors throughout the world. The activities of the agency will be conducted by a board of governors, which will include the twelve nations that worked out the provisional statute in Washington in the spring of 1956. At the United Nations conference in October, six other nations were elected to the board of governors—Argentina, Japan, Egypt, Peru, Indonesia, and Pakistan. At the time the final statute was adopted many of the delegates paid high tribute to President Eisenhower, who had of course presaged the formation of the agency in his speech before the General Assembly in December 1953.

The major difficulties that came up during the month's discussion at the UN had to do primarily with possible measures for insuring that the agency would not be inadvertantly helping individual nations to make atomic bombs. It was clear that there was no simple, practical way to insure that individual nations did not turn their knowledge to military purposes, yet it was clearly recognized that this possibility should not stand in the way of furthering the spread of atomic benefits. There was some disappointment expressed by the representatives of the Soviet Union and of India that Communist China was not a member of the conference or of the agency. Nevertheless, these objections did not stand in the way of the final unanimous approval of the 82 nations—a monument to the close coöperation that is now characteristic of atomic energy, as well as a significant ray of hope for future world-wide understanding and trust. In February 1957 the Soviet Union became the first nation to ratify the statute of the agency.

So far, independently of the International Agency, the United States, as well as other countries, is going ahead with plans for helping individual atomic "have-not" nations on the bilateral basis, or for coöperating with entire groups of countries. Thus the

United States intends to aid the Colombo Plan nations by supporting an Asian Nuclear Research Center that is now definitely scheduled for construction in Manila. The United States also organized an Inter-American Symposium on Peaceful Uses of Atomic Energy held in May 1957 at Brookhaven Laboratory on Long Island; this conference was very similar to the Geneva Atoms-for-Peace meeting, but on a smaller scale. European nations will pool their atomic resources in the organization known as Euratom; this plan will enable the construction of common facilities for fuel processing, for example, which would be extremely expensive for individual countries to build.

It is not clear how these arrangements, made independently of the International Agency, will be coördinated with the efforts of the Agency when its active existence begins. However, it seems extremely likely that the purpose of the United States is to fit these activities into the International Agency, which may in fact take them over completely. But whether on a bilateral or international level, there can be no doubt that atoms-for-peace is rapidly becoming a reality on a world-wide scale. The contacts made at Geneva are expanding by means of exchanges of reports and scientists between the East and the West, publication of results is now widespread, and recently active planning has started for another large conference at Geneva, to be held in September 1958, commonly called "Geneva II."

CHAPTER 8

SAFETY, SECURITY, AND THE AEC

We must learn to think rather less of the dangers to be avoided than of the good that will lie within our grasp if we can believe in it and let it dominate our thoughts.

—BERTRAND RUSSELL,
IN J. R. NEWMAN, ED., *What is Science?*
(SIMON AND SCHUSTER, NEW YORK, 1955)

In the United States the Atomic Energy Commission has the primary responsibility for the many technical aspects of atomic-energy development, destructive as well as beneficial. In addition, it must face the broader and more difficult problem of accelerating the practical realization of the benefits, while avoiding the potential harm. Although many agencies, governmental and nongovernmental, are concerned with the ramifications of atomic energy, the Atomic Energy Commission performs important functions in almost every phase.

We have been concerned throughout our volume so far almost completely with the present and future benefits of atomic energy; we must not forget, however, that this new factor in our lives has dangers that parallel its great promises. We are not here thinking so much of the obvious danger of atomic warfare as of those hazards closely connected with the peacetime uses of atomic energy. The danger of atomic warfare is much more than a technical question, involving as it does all the complex issues of foreign policy. The fundamental control problem with regard to military uses of atomic energy is one of avoiding war, with particular reference to atomic war, rather than a technical matter of atomic energy. These broader aspects of atomic disarmament are matters that are handled primarily by the top levels of government administration—by the State Department and the United States representatives at the

United Nations. However, even in these broad issues the Atomic Energy Commission has an important role to play, for it must supply technical advice, advice that often must verge on policy as well, for the use of the agencies concerned.

In our consideration of the various dangers of atomic energy, and of what we have done in the past and must do in the future to avoid them, we shall first examine in general the harmful effects of radiation. These are the results produced in living tissue, regardless of the origin of the radiations, whether from peacetime atomic reactors, bomb tests, or bombs used in warfare. We can then see what steps are being taken to minimize the dangers inherent in atomic energy as it is used in the rapidly expanding peacetime applications. Next we shall turn to another kind of safety, which is also an important concern of the AEC, the safety of our program relative to potential enemies—in other words, the matter of security. Here a fundamental question emerges concerning the various modes of attaining security, whether we maintain our lead over other countries by forging ahead as rapidly as possible or by keeping our work under close rules of secrecy, methods that to some extent are diametrically opposed.

Finally, at the end of the present chapter, we shall summarize briefly the way in which the United States Atomic Energy Commission has attempted to solve these difficult problems of attaining balance in the 10 years or so of its existence. The nature of the Commission and its operations are a matter of prime importance to all citizens, because it is through the Atomic Energy Commission that the vast sums of money invested by the American public in atomic energy will be wisely or foolishly spent. Thus it becomes a clear duty of all of us to examine carefully the manner in which the Atomic Energy Commission is using the money entrusted to it, so as to make intelligent decisions about the future course of the Commission. In this way we shall determine the future of atomic energy not only in America but to a great extent throughout the world as well.

The Dangers of Radiation

The mechanism by which the various radiations associated with the chain reaction affect living things is basically the same, whether the source of the radiations is a peacetime atomic-power plant or the radioactive fallout from a bomb explosion. Whereas the extent of the effects produced can be tremendously different in the two cases, the basic phenomena involved are identical. It is not our purpose to consider the detailed reactions by which A-bombs, H-bombs, and their variants produce such high intensities of radiations. These radiations themselves, which affect tissues in a variety of ways, are the same as those we have already described in connection with the beneficial uses of chain reactions, namely the alpha, beta, and gamma rays, and neutrons.

In connection with the dangers of atomic energy, we are interested in the basic changes that take place when these radiations penetrate living tissue. The intensity of radiation may be so small that the effects produced are negligible as far as their practical results on living matter are concerned. However, even these small amounts of radiation may be large compared to the magnitudes we have already considered in connection with the use of radioactive tracers. As we remember, tracers are useful for the very reason that the amounts involved are so small that the radiations produce no harmful effects. We must now examine the detrimental changes, not produced with the insignificant amounts of radioactivity used in tracer research, but arising with exposure to much larger radiation intensities.

When radiations encounter living tissue, the initial action is much the same as it is when a particular type of radiation is used to detect a radioactive tracer. In each case the primary action of the radiation is to remove some electrons from atoms, and thus to create electrically charged *ions.* In tracer research the creation of these ions can cause an electrical pulse in a Geiger counter and thus manifest the presence of the radiation. In living tissue the ionization can cause a chemical change within a cell, perhaps killing the cell or, potentially much more serious, causing it to behave in a manner radically different from normal.

The changes produced in a living cell by radiation are actually secondary results of the modification of the configuration of the electrons surrounding the atoms of the cell. This change in electronic structure, hence in cell behavior, is produced much more effectively by a particle carrying an electric charge than by an uncharged particle, because its charge interacts strongly with that of the electrons. Thus a neutron or a gamma ray, neither of which is electrically charged, produces many fewer ions, that is, affects the electronic structure of atoms much less, than the particles carrying an electric charge, such as the beta particle or the alpha particle. The charged particles in themselves differ widely in the number of ions they produce, the alpha particle, for instance, leaving a dense wake of ionization in its path compared to the lightly ionizing beta particle, but the effects on cells are still basically the same in kind, although possibly differing greatly in degree. The most direct effect of the changes in electronic structure produced in the atoms of the cell is the destruction of the cell itself, the straightforward effect that is utilized in the treatment of cancer by radiation. The principle here is simply to get the radiation to the cancer cells while causing only minimum damage to the normal cells. We have already seen how this preferential irradiation can be performed by placing the radioisotope in the proximity of the cancer cells and avoiding the healthy tissue as much as possible.

Planned use of radiation to destroy malignant tissue involves the same basic process that takes place when tissues are destroyed by accidental overexposure to radiation, to the explosion of an atomic or H-bomb, or to the radioactive debris present as fallout. Chemical changes, that is, alteration of electronic structure by the radiation, cause death of the cells if they are sufficiently extensive. Tissues in the body vary tremendously in their sensitivity to radiation, however, one of the most sensitive being the cells of blood itself and the blood-forming tissues. Thus when the body receives a severe dose of radiation there is an extremely rapid decrease in the number of red cells and white cells in the blood. Because of the important function of the white cells in combating infection, a serious secondary effect of radiation is that the white cells are not available to fight infection. In the circumstances, death may result from what would otherwise be relatively minor infectious diseases. It is certain that many of the deaths at Hiroshima and Nagasaki resulted from this kind of secondary effect. Another common result of overexposure to radiation is loss of hair, which can result from doses of radiation that do not produce other marked effects; in this case the loss of hair is usually temporary.

In addition to the simple death of the cell that we have been considering, a more complicated and in many ways much more serious effect is that, though the cell continues to live, its life history is profoundly affected by the radiation. In ways that are not completely understood, radiation may change the growth of a cell so that it becomes the beginning of the *malignant,* or uncontrolled, growth known as *cancer.* The production of cancer by radiation in this way has been known for a long time, in fact since the use of radium and similar materials in painting watch dials led to the tragic deaths of many of the workers. In these cases the radioactive materials, here alpha emitters, were deposited in the bone marrow and there caused cells to change in such a way that fatal bone cancer was produced.

A similar situation existed with regard to the miners of radioactive materials in Europe early in this century when the dangers of radioactivity were not known. According to a recent British report, nearly half of the miners working with radioactive materials at this period died of lung cancer. These cases followed the inhalation of the radioactive gases associated with the minerals and the resulting intense alpha-particle bombardment of the lung tissue when the gases were absorbed in the lung. A particularly unfortunate aspect of the origin of cancer by radiation is that an extremely long *latent period* occurs before the cancer becomes observable; in the case of the miners, for example, it was about 17 years on the average. The workers who painted the watch dials and died of bone cancer lived for periods ranging from 3 years to longer than 15 years after the exposure to the material before succumbing to bone cancer.

Before the dangers of radiation were fully known, x-rays were used to a great extent for a number of applications and individuals often unwittingly received serious doses of radiation. There actually is a significant difference in the length of life of doctors who have spent much of their time giving x-rays to patients, as compared to doctors not exposed to x-rays. The average life of the radiologists is significantly less, by about 5 years, than that of the unexposed doctors. In another connection it is now definitely established that *cataracts* of the eye result from radiation, in this case the sensitivity to high-energy neutrons being particularly great; several scientists developed cataracts by exposure to cyclotron neutrons before this danger was recognized.

Another malignant disease that is definitely connected with radiation is *leukemia,* in which the number of white cells is produced in the formation tissue of the bone marrow at a rate much higher than normal. For example, the occurrence of leukemia in the Japanese at Hiroshima and Nagasaki who were exposed to the bomb radiation is about four times that of the people in the same cities who were not exposed to radiation. The use of x-rays for treating various diseases, particularly in the period when the dangers of radiation were not too well understood, has been a very unfortunate source of evidence of the effects of radiation on human beings. For a number of patients treated with x-rays for disease about 20 years ago, it has now been shown that they developed leukemia with an occurrence rate about ten times normal. Also, cancer of the thyroid has been known to develop in young children unfortunately irradiated with x-rays for various lesser ailments, such as bronchitis or infected tonsils. For those cases that seem definitely radiation-induced, the thyroid cancer developed about seven years after the x-ray treatments.

Radiation and Genetics

In addition to the direct destruction of cells and the change in growth of cells exemplified by the development of various kinds of cancer that we have considered, there is another effect of radiation that is even more subtle in its appearance, more difficult to understand, and hence more uncertain with regard to the establishment of safe limits of radiation. This final radiation effect that we wish to consider is difficult to analyze because it does not affect the individual who is irradiated but his children or, more likely, his descendants several generations removed. This is the *genetic effect* of radiation, resulting from changes in the germ cells, changes that are propagated from generation to generation, unaffected by the death of the individual receiving the radiation.

The way in which characteristics are handed down from generation to generation via the *genes* in the germ cells is now reasonably well understood, and in fact is applied practically in the breeding of animals and of plants. Characteristics such as color of eyes, color of hair, intelligence, and tendencies toward various diseases are determined by the tiny genes in the germ cells. When an egg is fertilized by a sperm at conception, the genes from the male and female are mixed in a statistical manner and this statistical mixing produces the rather large variation in characteristics that exists in the offspring. Actually, the process of evolution is basically one in which the variation produced in this statistical way by mixing of genes is used to improve the species. The types best able to survive will tend to produce more offspring and the types less able to survive because of their particular combination of genes are more likely to die out. Thus in a very slow way the statistical mixing of genes plus the selection of the superior individuals will tend to improve the species.

In addition to the statistical combinations of genes just described, individual genes themselves can change as a result of various physical causes and perhaps can even change spontaneously; these changes are known as *mutations,* and they provide an additional source of new characteristics in a species. When a particular gene is changed in a germ cell the characteristic for which that gene is responsible will be changed in some way. Furthermore, all future germ cells resulting from the particular one in which the mutation took place will contain an altered gene. The reason for the maintenance of the gene change or mutation is that germ cells produce more germ cells by division, or *mitosis,* and in the division the genes reproduce themselves exactly. No matter how many thousands of divisions occur, the genes will always remain exactly the same, unless a mutation should occur, in which case the altered gene persists.

The production of identical germ cells by division does not imply that individuals of each generation will uniformly carry a particular modification, such as a change in hair color, resulting from a given mutation. The reason is that the changed gene combines with other genes at conception in the statistical manner already described. It is the particular *combination* of genes from egg and sperm that produces the obvious physical characteristics of the offspring, even though the individual genes are unchanged in the process. Nevertheless, the change in a gene resulting from mutation becomes part of the genetic heritage, just as for an unchanged gene, and it remains thereafter unless *all* individuals possessing this changed gene fail to reproduce, for it is only by this "genetic death" that a particular gene is eliminated. Many changes in genes produce such minor effects that they could hardly be noticed; on the other hand, other mutations may cause such great changes that the cell fails to reproduce, hence the mutation is not carried on, but suffers genetic death. Gene mutations are a matter of serious concern because by far the greater proportion of them are harmful changes, only a very rare change resulting in an improved characteristic. It is not surprising that the mutations are usually detrimental for they are a matter of chance in a gene pattern already highly developed by natural selection.

Of course it is the beneficial gene mutations, rare though they may be, that improve stocks. Actually, they have been utilized for centuries in the improvement of plants and animals by selective breeding. At the present time, selective breeding can be accelerated greatly because the rate of mutations can be increased by radiation. Extremely high radiation intensity will, of course, kill the germ cells outright, but lower doses will cause gene mutations without affecting the ability of the germ cells to reproduce. A large amount of experimental mutation work by radiation is now going on, especially in agriculture where it is rather simple to increase the number of mutations by the radiation of seeds, and to observe the resulting characteristics in the growing plants. The plants resulting from the irradiated seeds are watched carefully for improved characteristics, and these plants are then bred carefully to maintain the change. Practical results have already been obtained in this way and some strains of plants produced by radiation mutations are now in commercial production.

It is because radiation can produce gene mutations, and in such large numbers at high irradiation rates, that the entire problem assumes serious proportions. Most gene mutations are deleterious, hence we cannot blithely say that radiation-induced mutations are not harmful at all because they actually accelerate the process of evolution. This view is not correct simply because of the great preponderance of harmful mutations. The few beneficial mutations benefit the species only if the many harmful ones are eliminated by the failure of the individuals carrying them to reproduce. Under conditions of modern life, it is not at all certain that this "natural" selection process operates effectively for mankind.

When we consider the safe limits of exposure relative to genetic effects we are talking about intensities well below those that would occur in an atomic war. The latter intensities are so enormous that it is hardly necessary to consider whether bomb radiations exceed safe limits for genetic effects; they far exceed these limits as well as limits for many other effects that require much higher radiation intensity. Rather the question concerns the year-in-year-out use of atomic energy in peacetime applications. In this routine use of the chain reaction, it is extremely difficult to decide how much radiation can safely be absorbed by human beings. Here we are considering the safety of many, many generations yet to come, and with regard to effects only dimly understood at present. However, let us now look at the way in which "safe limits" of radiation are fixed, in spite of insufficient knowledge, and how safety in the peacetime use of atomic energy is being attained.

Safe Limits of Radiation

In connection with the peacetime applications of atomic energy, there are many ways in which human beings might obtain excessive amounts of radiation. Thus during the operation of reactors, personnel might be overirradiated if the shields around the reactors are not sufficiently thick. This difficulty is not in practice a very serious one for it is a relatively easy matter to design adequate shielding. However, there are indirect ways in which radiation can be received from reactors and these are somewhat more difficult to handle.

For example, in the case of a gas-cooled reactor there is the hazard of the gas emerging from the reactor. Some of the early reactors are cooled simply by forcing air through the reactor core and allowing it to escape to the atmosphere. Usually the emerging radioactive air rises high enough into the atmosphere that the radioactivity dies away before harmful amounts are deposited on the ground. In unusual weather conditions, however, the radioactivity may return more quickly to the ground, being carried down by rain, for instance, and harmful amounts of radiation might result. Another hazard arises from the large amounts of radioactive waste material developed in reactors, primarily the fission fragments. Thus we have with us an ever-increasing problem of the disposal of these radioactive materials. If they are stored in an inaccessible place sufficiently long the radioactivity dies away, but unfortunately some of the fission fragments have extremely long half-lives and will remain radioactive, in some cases, for thousands of years. As a result, the radioactive wastes cannot simply be dumped in the ocean, for even if they are held securely in containers for many years they could do harm after escaping and being dispersed widely by ocean currents. A great and largely unknown additional difficulty arises from the fact that certain forms of animal life tend to accumulate particular chemical elements; if these elements are present in the radioactive fission products, the radioactivity can be concentrated greatly. If, for example, this concentration is done by some form of edible fish, human beings might therefore ingest an amount of radioactive material much greater than that estimated on the basis of uniform distribution.

Here we are speaking of the more or less normal operation of reactors; there remains the question of accidents. For example, if a large atomic power plant should in some way explode the amount of fission fragments thus released would constitute an extremely great danger if spread throughout the surrounding community. Likewise, if radioisotopes are being transported from the reactor where they are made to laboratories where they are used for research or treatment of disease, they constitute a potential hazard and must be carefully handled in the process so that they do not contaminate the surroundings.

In assuring safety in the use of atomic energy it is necessary first to decide how much radioactivity of various types can be administered to human beings without harm resulting, for without some knowledge of these limits it becomes very difficult to plan practical methods of radiation safety. The safe limit of radioactivity is expressed as a *tolerance dose,* this amount being considered the level of radiation to which an individual can be subjected indefinitely with no adverse effects. The tolerance dose is usually expressed as an amount that can be safely absorbed in a given length of time. In principle, it would be necessary to specify the tolerance amount not only for each particular kind of radiation, but for each tissue in the body, because the harmful effects vary with the kind of radiation, and the sensitivity of the various tissues differs greatly even for a single radiation type. However, we do not need to concern ourselves at this point with the complications of these variations, for we are interested in the limits as applied in practice.

The radiation *dose* is quoted in terms of a unit called the *roentgen* in honor of the physicist Roentgen, who discovered x-rays. The roentgen, or r, is an amount of radiation, although as actually specified scientifically it is defined in terms of a certain amount of ionization produced by the radiation involved. It is necessary to work out rather elaborate formulas to convert from one type of radiation and one type of tissue to others but it suffices for us to realize that the radiation doses are expressed in roentgens or in a much smaller unit, the *milliroentgen,* or mr, which is 1/1000 of a roentgen. Thus the tolerance dose of radiation for those working in atomic-energy plants at the present time is 300 mr per week, and a careful check is made of the workers in these plants to see that they do not exceed this limit. The check is made by small instruments that record the amount of radiation received, instruments so small that they resemble closely a fountain pen in size and shape. They are worn at all times and are read periodically to determine the amount of radiation received. Some of these radiation meters indicate by a dial just how much radiation has been received; others must be placed in a voltage-measuring instrument for the determination.

It is one thing to decide what workers in atomic-energy plants may safely absorb in the way of radiation, but when the entire population is considered, and in particular when genetic effects to all mankind are the deciding factor, the question becomes much more difficult. With regard to the genetic danger, the important matter is the total amount of radiation received by an individual from the time he is born until he conceives no more children, say a period on the average of about 30 years. One way to decide how much radiation can safely be absorbed by the population as a whole during this reproductive period is in terms of the amount relative to the *natural rate* of gene mutation, the rate at which mutations occur naturally, in the absence of radiation. This computation involves many relations and poorly known ones, but at the present time the best estimates are that the gene mutation rate would be doubled if the population as a whole should receive about 50 roentgens per person during the 30-year reproductive period.

We realize how small is this 50 r per lifetime dose if we simply compare it with the 300 mr per week that we have mentioned for atomic-energy plants, which would be 15.6 r per year or 468 r in 30 years—ten times the amount that would double the mutation rate. These limits that we have quoted for workers at atomic-energy plants are much higher than for the average of the population, because the change in the genetic make-up of an entire population depends on the *average* radiation received by the population, rather than that received by particular individuals. Actually the most recent recommendations for the population as a whole are that *on the average* less than 10 r should be absorbed by age 30, and that for *individuals* the amount should be kept less than 50 r by age 30 and less than another 50 r by age 40. These low tolerance levels are recommended primarily because of the serious and widespread results of genetic changes induced by radiation. The recommendations indicate the extreme seriousness with which the genetic situation is viewed at present and emphasize that extreme measures must be taken to insure that the genetic effects of radiation do not produce great harm in generations far removed in the future.

Radiation Protection and Insurance

In connection with the peacetime pursuits, such as production of electric power and use of radioisotopes in research, there is no reason in principle why the limits of radiation cannot be kept to the recommended figures. We say "in principle" because we do not wish to imply that keeping the radiation down to these values will be easy, but only that it is possible to lower the radiation to almost any desired value by taking more and more elaborate precautions. Nuclear reactors can be shielded to almost any degree so that the workers near them will receive very small amounts of radiation. Operations with reactors, such as removal of radioisotopes, can be carried out with special instruments and protective clothing, as shown, for example, in Fig. 44. Radioisotopes can be shipped in sufficiently large containers and handled with remote-control equipment so that the workers will not get irradiated.

However, in this matter of radiation protection a sound balance must be attained. We cannot simply say we must make rules so that irradiation is kept down to an extremely low, arbitrary, value for this would make many operations so expensive that they simply could not be carried out. Even in the absence of atomic energy, mankind is subjected to some radiation, the energetic particles, for instance, entering the earth's atmosphere as *cosmic rays,* or the radiations present in small amounts of all material, resulting from such impurities as uranium and radium.

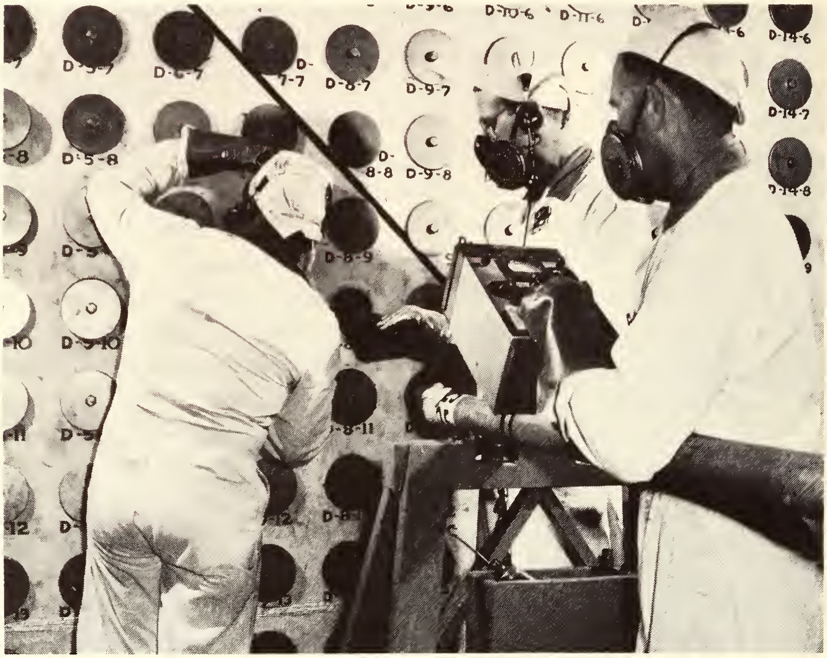


Fig. 44. The use of protective clothing while working at the Brookhaven reactor; even though the reactor is not in operation during the work, the presence of residual radioactivity makes extreme caution necessary.

In addition to the provision of maximum safeguards so that individuals will not be exposed to radiation, attention must be paid to the possibility that, in spite of the safeguards, radiation-producing accidents can occur. Remote as the possibility of a large accident with a reactor might be, it is nevertheless necessary for the companies that are to build these reactors to envisage the possibility of such a catastrophe. If a large power plant should be destroyed in such a way that the contained radioactivity were spread over a densely populated area, the damage to individuals would be very great. The matter of insurance to cover an accident of this magnitude becomes in itself a problem almost impossible to solve under existing insurance structure. At the present time, estimates of the possible financial risk involved in a large-scale catastrophe range as high as several hundred million dollars, more money than could be supplied as insurance even by groups of insurance firms in the United States.

The difficulty of insuring large plants against such catastrophies is sufficiently great that in a real sense the failure to find a way to supply the insurance is having a deterrent effect on programs for constructing such large power reactors. It is not that large risks are unprecedented in industrial processes; it is just that atomic energy is being developed so rapidly that there is very little applicable experience to aid in deciding the correct way to organize the insurance coverage. The consensus of opinion at the present time among the experts in the insurance field is that private companies can hardly be expected to take on the large risk involved and almost certainly the government will have to step in, probably to handle the risks of magnitude greater than can be covered by combinations of private firms. In May 1956, the Nuclear Energy Property Insurance Association was organized by 155 stock property-insurance companies in the United States. This group can supply up to $50 million in property-damage coverage alone. This development is a great help but the amount is still not high enough to cover a major disaster. Third-party liability coverage is also definitely needed but, although recommended by the Joint Committee on Atomic Energy, Congress did nothing to supply it in 1956. Plans are before Congress again in 1957, however, and probably some form of government insurance will be established before long. It is only after experience has shown how the large plants will operate that it will be possible to handle the insurance as it is managed in conventional plants, such as large chemical factories, which also have definite hazards connected with them, handled by private insurance companies.

Safety in Bomb Tests

At the present time much serious consideration is being given to the possible harmful effects of the radiation resulting from the tests of A- and H-bombs. It is true that during the presidential campaign of 1956 the issue of "halting H-bomb tests" became thoroughly involved in campaign matters, but this does not detract at all from the fact that the problem is an extremely serious one and does require careful thought on the part, not only of scientists, but of intelligent citizens throughout the world. As we are concerned with the peacetime applications of atomic energy, it is not appropriate for us to go into the question of the various types of bombs and the amount of radioactivity they release, nor such questions as the extent to which the radioactivity resulting from a bomb can be controlled, the so-called "clean" bomb. It is also true that the bomb tests do very little to advance the peacetime applications of atomic energy; thus as far as our primary interest, atoms for peace, is concerned, the bomb-development program adds very little. However, some consideration of the dangers of bomb testing is well worth our while. Not only do the considerations here illustrate the type of danger that may be present from peacetime reactors, even if bomb tests should end, but the tests are certainly an activity during peacetime that cannot easily be dismissed, and therefore that must be reckoned with if we are to attain the benefits of atomic energy without unduly increasing its risks.

The dangers from the radioactivity produced in a bomb come primarily from the radioisotopes that are released into the stratosphere and dropped to the earth, some very rapidly after the bomb's explosion, and some even years later, this radioactivity being known commonly as *fallout.* The radioisotopes in the fallout are those already familiar to us from our discussion of the use of radioisotopes in research and medical treatment, the difference being that their amounts are vast compared to the ones used in normal research and treatment. It follows that the effects of the radioactive fallout are very much the same as we have considered in the use of tracers or in our discussion earlier in the present chapter on the general dangers of radiation—they can destroy cells, they can produce cancer, they can cause long-lasting genetic effects.

As bomb testing increased in tempo and in size of bombs through the years since the first test in 1945, more and more comment was engendered concerning the possibility of stopping the tests, not only as a move toward disarmament but because of the dangers resulting from the large amounts of radioactivity being released into the atmosphere, to be received throughout the world as fallout. Although some of these suggestions no doubt properly belong in the realm of world propaganda, many expert and level-headed scientists felt that careful attention should be paid to the problem, lest we unthinkingly harm many generations to come.

As a result of suggestions from many organizations and individuals made in the early fifties, a committee of the National Academy of Sciences of the United States was appointed to study the dangers of ionizing radiations. This committee issued its report in the summer of 1956 at the same time that a similar report was issued by a committee of the British Medical Council. Many aspects of radiation were considered: the effects on genetics, harm to living people (pathology), meteorological effects, effects on fishes and agriculture, and the disposal of radioactive wastes. The reports of the committees stressed particularly the question of genetic effects and the far-reaching results of radiation-induced mutations. It was because of these serious genetic considerations that recommendations were made concerning the average dose for the population as a whole. We have already described these suggestions, which are expressed in terms of the allowable radiation dose over a 30-year period.

In general, genetic effects were considered most serious, that is, they would set the tolerance dose on the amount of allowable radiation, the genetically determined dose being much lower than the safe dose determined by other damage. The case of *radioactive strontium,* however, which aroused so much interest during the 1956 presidential campaign, is an exception, in that here the danger to individuals now living is the primary concern. The danger of radioactive strontium is particularly great because one of its isotopes has a long half-life, 25 years, and because, like calcium, it is deposited in the bones when it is ingested. There it will remain for the life of the individual, and it can cause bone cancer much as radium did in the bones of the workers who painted watch dials. However, the danger is very uncertain because of the difficulty of estimating how much of the radioactive strontium will eventually be deposited in human beings.

Although the amount of radioactive strontium already released by bomb tests is small averaged over the population of the earth, danger arises because the possibility of concentrating the strontium is strong. For example, radioactive strontium has already been found in the milk from cows that grazed where radioactive strontium had fallen on the grass. If children who lack calcium should drink this milk, a large fraction of the radioactive strontium would be deposited permanently in the bones with possible grave effects. A recent report reveals a slow steady rise in the amount of radioactive strontium in milk in the St. Louis area, although the amount is still well below the tolerance dose.

Even though the amount of radiation so far released by bomb explosions seems well below the safe limit, the situation in the future is no certain matter. In order to fix the scale it is well to give a few numbers for the nonbomb radiations that we are all subject to at the present time. Taking an average of the American and British reports, we find that the ordinary *background radiation,* that coming from *natural sources,* such as radioactive material in the soil, cosmic rays, and so on, is about 4 roentgens for the reproductive period of 30 years of an individual's life. The additional radiation received on the average because of medical and dental x-rays is about 2 roentgens, making a total of 6, which is by no means small compared with the recommendation that the average individual should get no more than 10 r during the first 30 years of his life.

Compared with these sources of radiation it is estimated, actually with great uncertainty, that an individual will receive only one-third roentgen in 30 years at the present rate of bomb tests. This is small compared with the natural background rate or that resulting from medical and dental x-rays, but the possibility of an increase in the rate of weapons testing is an extremely strong one. Thus from the numbers we have already discussed we conclude that an increase in the rate of weapons testing by a factor of 150 would bring the average radiation rate for all people on the earth to the figure that is necessary to double the natural mutation rate. This doubling of the natural mutation rate can be considered a very serious matter. For example, at present about 4 percent of babies born in the United States have definite defects of a genetic nature. Doubling the number of children born with such genetic defects represents a tremendous number of observable deleterious effects of radiation. Fortunately, it now seems extremely unlikely that the rate of radioactive fallout will increase markedly, because of the effect of international study groups and the development of "cleaner" bombs.

Security and Achievement

In the last section we discussed those aspects of the continued testing of bombs that are primarily concerned with the radiation damage to human beings. We have not touched on the broader and more complicated issues involved in bomb testing, such as the necessity of developing bombs as a means of attaining national security. It is inappropriate to our present purpose to go into the political and moral matters concerning the foreign policy of the United States and the relation of bomb development to disarmament in that policy. However, one aspect of the military application of atomic energy is definitely our concern—the matter of security and the effort to attain it by secrecy. The reason is simply that steps taken to maintain our national position in military strength inevitably have a very direct effect on the development of peacetime atomic energy. It is not only a matter of competition for money and men, but the competition of secrecy and achievement.

The whole thorny question here, and one that is of great importance to the successful development of atomic energy, is to avoid the handicaps should we endeavor to maintain our position relative to other countries, in particular potential enemies, by keeping our progress secret. It is true that we may retard their progress in this way, but perhaps with a concurrent blocking effect on our own program because of the secrecy restrictions. The important issue is, no doubt, security. However, it is security not only in the simple sense of maintenance of our secrets, but the security of our entire nation and the way in which *all* phases of our atomic-energy program are related to this broader security. It is necessary to look into these matters to some extent; only with a sound understanding of the principles involved can citizens aid in the handling of atomic energy in such a way that our security is maintained, with a minimum of stultifying effect on the applications of atomic energy to the betterment of our lives.

The concept of security as applied to atomic affairs produces many complicated effects, effects that can hardly be understood without a consideration of the concept of security itself. For an individual, the meaning of security is somehow related to maintaining the things that are important to that individual. His security includes confidence in the continued possession of the things that are important to his leading a good life, such as physical property, health, and intellectual and religious freedom—with all these things in varying proportion depending on the particular individual. His security in these possessions follows partly from laws designed for their preservation, as well as from his own preparative efforts, in the way of education, insurance, and maintenance of health.

As far as the security of a nation is concerned, which is the type of security so intimately connected with atomic affairs, the situation is analogous. National security refers to the preservation of those things that are considered by the citizens to be the important components of national life. The immediate good that comes to mind relative to national security is, of course, the preservation of the nation itself against foreign conquest. On further thought, however, it is clear that of almost equal importance, or perhaps part of the very preservation of the nation, are such things as the freedoms protected in the Bill of Rights and the national strength that comes from the free exercise of the abilities of all the citizens.

In most discussions of security as related to atomic affairs, the security of the nation itself, in the simple sense of its preservation, is the primary issue. The unqualified, misleading proposition is usually inherent in the discussions that we will be secure if somehow we keep our secrets inviolate. This concept of security leads to an identification of security with secrecy and to such simple conclusions as that we are more secure the more we withhold our information, or that any information that reaches our potential enemies weakens our position relative to theirs. When the broader meaning of security is considered, however, involving the totality of means necessary to preserve the kind of national life that we desire, the simplified identification of security with secrecy disappears. We then realize that in many cases withholding information may actually be a step toward insecurity rather than the reverse. The reason here is simply that the true security of the nation arises from a great complex of factors involving our total strength relative to potential enemies. This strength is actually more rightly related to our positive accomplishments and our abilities in comparison with those of the potential enemy than to the elementary, narrow question of what he knows about our activities.

The broader view is actually a realization that there are positive aspects of true security as well as the negative one of secrecy, and that these are more important than more secrecy. The correct view of security involves what is often called "security by achievement" rather than "security by concealment." To illustrate: by mixing the meanings of the word security one could say that it is possible to obtain "security by insecurity," in other words, that true security can often be furthered by what would be considered insecurity in the narrow sense of security as rigid secrecy alone, that is, in a lock-and-key concept of security.

As security affects the day-by-day operation of atomic energy in America, it involves both people and documents. Personal security has evoked most interest in public discussion, but security of reports, data, plans, or *information security,* is of paramount importance in the attainment of true national security. It is interesting, however, that in both personal and information security the concept of negative and positive aspects just discussed plays an important role.

Unfortunately, in both branches of security, the negative aspects have tended to be emphasized in the past. This tendency has been revealed in personal security through the widely publicized hearings concerning *clearances* of personnel, necessary for participation in classified work. Here the negative emphasis results in a consideration primarily of the detrimental information about an individual, without balancing it against his positive contributions, which may vary tremendously with the man involved. This is the same effect that we have just described in information security, namely, the proposition that every bit of information should be firmly withheld from potential enemies because of its possible help to their program, without considering how release of such information might build our own strength with a much more important result on relative positions.

Atomic Security after Geneva

During the years leading up to the Geneva atoms-for-peace meeting in 1955 there was a gradual progression from the idea of information security as a negative concept to a realization of its important positive aspects. This realization coincided with the increasing importance of the nuclear chain reaction as a peacetime tool of wide applicability relative to its use as a means of wartime destruction. The positive aspects of security are now much easier to appreciate in connection with production of electric power and the use of radioisotopes than they were in the early days when the bomb was the only concern. While it is true that, considering bomb development alone, positive security is still of paramount importance, nevertheless the beneficial phases of atomic energy, when included in the considerations, make rigid secrecy much harder to defend as a means of security.

And now, two years after the Geneva meeting, it is clear to the world that we are sharing our vast information in the field of peacetime atomic energy, that we stand ready to help all nations and to be helped by them. At Geneva, and since, the steps taken by the United States indicate that we feel that, in the peacetime applications, we are depending on achievement, not on secrecy. As mentioned in the previous chapter, our information release and coöperative attitude at Geneva were matched, somewhat to our surprise, in every way by the Soviets. The most reasonable explanation for the Soviet coöperation at the Geneva conference is that the Kremlin, for whatever reason, had decided that coöperation, real and not mere window-dressing, was its best policy in this particular field. This decision does not necessarily imply similar coöperation in other spheres of activity, but let us value what we have attained and attempt similar attainments in other fields, rather than discard something of value by unthinking cynicism. Perhaps the Soviets have reached the conclusion, as we, I hope, are doing, that security by achievement, involving only strictly necessary secrecy, is the best policy for atomic progress.

It is appropriate now to consider whether, and how, we should modify our system of atomic security in the light of the happenings at Geneva. The United States work was certainly the outstanding contribution at the conference, but it does not follow that our security program of the last ten years is thereby justified and should be continued unchanged. Far from strengthening the old idea that the Soviets could accomplish little without aid from spies, the conference showed conclusively that the Soviets have advanced tremendously in the last ten years in atomic energy. As revealed recently in Truman's memoirs, Stalin had mentioned in 1945 that his scientists had been attempting to develop atomic bombs but hadn't gotten anywhere. It was a far different picture at Geneva; the Soviet scientists described work of a high technical level and, while somewhat behind us in most phases of the work, were forging ahead relentlessly.

Perhaps the strongest single impression carried away by American scientists from Geneva was this changed estimate of the Soviet position, the realization of the increasing technical competence of their work. This conclusion does not gainsay the vital effect of positive security, the acceleration of development when freed from the restraints of secrecy. Actually—and here it is difficult to give conclusive evidence without resorting to highly technical data—one strong factor in our own preëminence was the absence of secrecy in much of our own work, primarily in the basic nuclear physics involved in atomic energy. Our lead was greater by far in the fields that have been open in the United States but secret in Russia than in those phases that were secret in both countries before Geneva.

A somewhat surprising, yet vitally significant, fact follows from these relative standings. It is this: our greater lead obtains in spite of the complete availability of our work in these fields to the Soviets. The situation is striking proof of the way in which work in a secret field in Russia was retarded, even though in this instance the American work was completely available. What held back the Soviet scientists was the inability to discuss freely their own work with their colleagues, to receive the open criticism and careful weighing of results that occurs effectively only in an open situation.

Of course the lesson we have thus learned about positive security from Geneva cannot be applied in an extreme form; we cannot conclude that the entire atomic-energy program, bombs as well as reactors, should now be thrown wide open. It is true that every phase of the program would advance faster if it were unclassified, but on strictly military aspects the short-term advantage to us of secrecy must be weighed against the certain acceleration of declassification. Classification of the methods by which bombs are detonated to give maximum explosive efficiency, or of the rate at which we are making bombs—matters that could be of great importance should a war occur in a few years—is of obvious advantage to us. But as this classified information gives us at best temporary advantages, secrecy should be used only when we are willing to sacrifice the impetus to the development that full disclosure would give.

At Geneva we released large amounts of information important to peacetime applications of atomic energy, principally to the production of electrical power, while retaining information of strict military utilization. The distinction, while easily stated, is sometimes very difficult to make in practice. It becomes particularly knotty in the case of the large production reactors, such as the plutonium producers at Hanford. The detailed methods used to maximize the power level, hence the production rate, is here of obvious military significance, but of course the same considerations are of prime importance to civilian power reactors. Thus a continued, thoughtful reappraisal of the situation must be pressed, weighing the short-term necessity of military secrecy against the positive impetus of declassification.

The principle just stated, that we do better relative to other nations in a situation where all is open than under tight secrecy, which secrecy favors regimented methods, is fundamental to our major premise—that positive security is our greatest strength. It is primarily in a democracy that positive security will best prosper, and, as time goes on, our lead should be strengthened as we are able to bring more and more phases of our research out of the wraps of secrecy and into the full light of normal, free scientific interaction.

The Development of the Atomic Energy Commission

In a sense there is no need for us to devote a special discussion to the place of the AEC in atomic energy in the United States, for practically all of the activities we have described in this entire volume have been either a direct responsibility of the Commission or those in which it plays a definite role. There is scarcely any phase of atomic energy or its manifold applications that is not affected directly or indirectly by the Commission, even though we have not mentioned the connection explicitly in each case. Particularly in the present chapter, however, we have considered matters in which the Atomic Energy Commission performs some of its most difficult tasks—safety and security. Of course it is with regard to just these phases that the Commission is most likely to receive public criticism as well, because here it is closest to affecting the lives of people directly.

The dangers of atomic energy are such that they affect human beings in dramatic ways, and hence stimulate strong emotional reactions. Wide publicity is easily aroused by the dangers of radiation, and, because of the sometimes widely exaggerated possible effects, the Atomic Energy Commission is particularly likely to receive adverse comment. The correct balance between enlightening and foolishly frightening the public is difficult to maintain in information policy. Likewise, in establishing protective measures, the correct balance between protection of the public and unnecessarily elaborate safeguards that will cripple the atomic-energy program is even more difficult to attain. The same type of balance must be maintained in the matter of security, extending neither too far in the direction of ironclad secrecy together with the hampering of our program nor toward too little security and the danger of a real loss of relative military strength. The bomb-test issue, as we have seen particularly in the 1956 presidential campaign, has been a matter of widespread public interest and usually exaggerated reaction. In all these matters the Commission has figured prominently and has received probably much more blame than praise, a result often based on lack of information.

However, since it is practically the sole custodian of such a new and potentially dangerous as well as beneficial field, it is perhaps not surprising that the Atomic Energy Commission throughout much of its history has had controversy at its very core. In fact, it was formed in a period of great concern about the correct role of atomic energy in public and private activities in the United States. It was the extended public discussion attendant on the formation of the Commission that actually made many scientists realize their new importance and duty to the life of the country, in addition to their quiet pursuit of research. The great issue in the year 1945 was whether atomic energy should be turned over to a government commission from the army "Manhattan Project." At this time the definite possibility that atomic energy would be set up permanently under the control of the War Department, a step that was considered by most scientists to be a danger, thrust many of them into feverish political activity.

As the public at large knew of atomic energy primarily as a military weapon, it is not surprising that there was a generally accepted view that atomic energy should remain with the army. The scientists practically alone were in a position to realize that atomic energy had many potentialities more important than its use as a bomb, and that in a democracy civilian control was the only way to handle a tool of such tremendous peacetime possibilities. The manner in which the involved discussions were carried out, in public debate and congressional hearings, and a final solution reached, is an excellent illustration of how such controversies can be settled under a democratic system. The congressional hearings, even though bitter at times, did go thoroughly into all aspects of the atomic-energy program. The conclusion was finally reached that the only way to handle the new force was under civilian control, with effective liason with Congress and the Department of Defense. The result of these extensive hearings was the McMahon Act, passed in 1946, which set up the entire atomic-energy program in all its aspects under a five-man civilian commission.

The first Atomic Energy Commission, under the chairmanship of David Lilienthal, established the basic organization of the Commission and formulated many of its principles of operations, some of which still exist. The Commission from the first had wide powers, many of them unusually free from congressional check because of the highly classified nature of bomb development and production. The primary congressional control was carried on by the Joint House-Senate Committee on Atomic Energy, and the seriousness with which this committee approached its work was evident from the start and has continued ever since.

Throughout the history of the Atomic Energy Commission the program has advanced tremendously both in complexity and magnitude, as is borne out in all of our descriptions in previous chapters. This development has not taken place without controversy. For the most part, however, the disagreements, while time-consuming, have eventually had beneficial results, for out of them came improvements in the organization of the Commission, advances in the way in which atomic-power development is handled by it and by private industry, and a clarified view of the nature of security in atomic energy.

In the formative years of the Commission some differences in basic outlook of the Joint House-Senate Committee and the Atomic Energy Commission gave rise to increasing friction and finally culminated in the public investigation of "incredible mismanagement" in the Commission. These hearings, which continued a long time and, as is often the case, carried political overtones, resulted in a majority report that by and large exonerated the Commission from the strong charges made against it. However, without doubt the investigations had a certain beneficial effect in improving the organization of the Commission, and the constructive criticisms in the Committee's findings were of definite help to the Commission in carrying out its complex functions.

A problem that has involved much difficulty throughout the life of the Commission has been the proper balance between security of the country and the progress of basic science and development, which depends on freedom of communication. In this matter, although the path has been winding, and at times the criticism of the Commission on the part of scientists very great, in the main there has been steady improvement in the understanding of the problem and in the administrative procedures necessary for "clearance," with a minimum of interference with the program itself.

The revelation that spies, such as Allan Nunn May and Klaus

Fuchs, had given information of value to the Soviets had an understandably great effect in increasing the pressure for tight security restrictions on scientists and on technical data as well, an increase far out of proportion to the value of the information actually transmitted by these men. The high point in the matter of personal security came with the "Oppenheimer case," in which J. R. Oppenheimer, who had been head of the wartime Los Alamos laboratory, was denied clearance by the Commission, an action that was upheld by a review board in a lengthy hearing. The decision was criticized strongly by many scientists, primarily because of the conviction that, under the established clearance procedure, detrimental information could not be counterbalanced by an individual's positive contribution. Although it is undeniable that the extensive public discussion that took place at the time of the Oppenheimer decision helped greatly to clarify the issue and thus cause future improvement in the security system of the Commission, it is most unfortunate that the discussions could not have been aroused by the security problem itself, rather than by its manifestation for a particular individual.

Great improvements have since been made in the methods by which security cases are investigated and the hearings held, in the direction of decreasing the amount of harm to the individuals involved. In addition, the removal of security requirements for positions involving only unclassified data has gone a long way toward reducing the complicating effects of the security system on progress in basic research. On the other hand, as far as information security is concerned, many significant steps have been taken in removing material from the "classified" status. Thus at the present time many large fields in atomic energy are completely unclassified, and the research results obtained can be transmitted freely from the very start with no complicated procedures for declassification necessary. Actually, the security system of the Commission with regard both to personal and information security, is now regarded by many as the best of all the government departments, and a model to be used by the others. This state of affairs certainly does not mean that perfection has been reached, but definite progress has been made.

Current Problems of the Atomic Energy Commission

At the present time still another controversial item is engaging wide attention, and is the subject of much earnest discussion, as well as some irresponsible comment, as usual. This question concerns the proper way in which to push the development of atomic power in the United States, especially since foreign competition is increasing apace. Here the concern is primarily one of over-all policy, whether the United States should now build reactors that could produce large amounts of power, or whether the program should be mainly one of research, with greatly improved types of reactor developed before any large plants are constructed. We have already described various aspects of the technical matters concerned with the economic production of atomic power in Chapter 4, and want here to consider only the particular role of the Commission.

It is obvious that in this question, as for security and other broad policy matters, the function of the Commission is of tremendous importance in determining the future course of atomic developments. Again, deciding the best way in which to promote the program and take proper balance of the many conflicting forces is an extremely complex affair. At the present time, the Commission is receiving much unjustified criticism because, to the uninitiated, the fact that Britain now has a plant in operation, actually putting electric power into the grid, makes it appear that the United States is lagging. However, in line with our discussions in Chapter 4, we realize that this conclusion is unjustified, and that a true picture of the relative character of the programs in the United States and Britain must involve many factors other than the simple fact of a power reactor operating at the present time.

Actually, and unfortunately, the controversy over the correct manner in which to advance the development of atomic power is one that involves several long-standing controversies in the United States, and thus makes the problem even more difficult than it would be on a technical level alone. Thus, one recognizes the old problem of private versus public power, here exemplified in the planning of atomic-power plants—should they be built by private capital or under government sponsorship? It is certainly true that the expenditures for large power plants go beyond what can be handled completely under the methods of private enterprise, hence that the government should support the development. Furthermore, this new force for the betterment of our lives, whose initial development was obtained by public money, should be pushed rapidly by the government where necessary, simply because the public has paid for such a large share of it and deserves to get its benefits as rapidly as possible. On the other hand, it is clearly wise that large private companies should be called into the program, or encouraged to start their own, so that their eminently successful methods may push the entire effort. We are not far, as we have seen in Chapter 4, from the period when atomic power will be economically feasible. At this stage the development can hardly proceed rapidly in the United States unless the traditional American method of competitive private industry is functioning in an important way.

In the matter of organization of the power program, events are certainly not standing still by any means. In a speech before the American Nuclear Society on December 11, 1956, Chairman Strauss of the AEC announced that he was proposing that a large expansion in atomic-power development take place. He stated that to aid in the expansion there would shortly be a release of a large amount of technical data on power reactors. In addition to some eighteen civilian atomic power plants now planned, involving more than a half-billion dollars, he proposed five additional power reactors. These would be built by private industry, but if necessary the Commission would construct them. The release of data to which Admiral Strauss referred occurred a few days later, under declassification rules agreed on by the United States, Canada, and Great Britain.

Very recently the Commission became involved in still another controversy, this one magnified many-fold by its entrance as a political matter in the 1956 presidential campaign. This is the matter of the danger of radioactive fallout and its connection with the possibility of prohibiting tests of A- and H-bombs. As we have seen, the amount of radioactivity resulting from fallout from the bombs already exploded is very small compared with other sources of radiation to which we are already exposed. The danger that must be constantly kept in mind, however, is that of continued or even expanded bomb tests. Actually, there is very little disagreement at present among scientists concerning the amount of radiation resulting from fallout, and that *some* danger, however slight, is caused by it. The controversy really centers on the ethical question of balancing this danger against that of hindering development of an important deterrent weapon. Fortunately, the radiation committee of the United Nations, established directly at the suggestion of the United States, is now operating successfully and seems to be receiving the complete support of both Eastern and Western nations. It seems extremely likely that the findings of this group, with regard to necessary steps in bomb testing to insure the safety of both the present world's population and future generations, will be implemented by all nations.

Thus, in this problem of fallout, as in power development, security, and military control, we find that informed public opinion, open discussion, and careful investigation, even though accentuated and perhaps even promoted by strong emotions, are leading the way to a realization of the potentialities of atomic energy for the enrichment of man's life.

CHAPTER 9

FUSION

I venture to predict that a method will be found for liberating fusion energy in a controlled manner within the next two decades. When that happens, the energy problems of the world will truly have been solved forever, for the fuel will be as plentiful as the heavy hydrogen of the oceans.

—H. J. BHABHA, OPENING ADDRESS OF
GENEVA CONFERENCE, AUGUST 8, 1955

And now that we have concluded our examination of the ways in which fission is being turned to the betterment of mankind, and the extent to which this new force is already entering our lives, we turn to the more remote future—to the possibility that someday fusion as well as fission will be providing better lives for mankind. We have purposely delayed our consideration of the possibility of peacetime uses of fusion until we have considered all of our discussion of fission, for peacetime fusion uses are sufficiently remote that consideration of the uses of fission can, and should, be made with no interference arising from the possibility that fusion power will soon be with us.

Actually, and somewhat unfortunately, the use of fusion as a possible source of power was introduced at the time of the Geneva atoms-for-peace meeting and tended for a few days to complicate the discussions of fission as a power source. The introduction was unfortunate, for the use of fusion is so far removed from practicality relative to fission applications that its possible role in the future should not interfere with present-day planning for power and research uses of fission. Fusion energy has of course been successfully released in the form of the H-bomb, but to date there has been no release of this enormous source of energy in a controlled manner. In the present chapter we shall, however, consider the nuclear processes involved in the fusion reactions, and the possible ways of achieving controlled fusion power. Using the basic nuclear physics of Chapter 2, we can easily study fusion in sufficient detail that we can understand the techniques by which fusion might be introduced as a power source. Thus we shall be prepared to estimate how it might ultimately affect our lives and the extent to which it should enter, if at all, the plans for uses of fission energy.

Principles of Fusion

It is a property of nuclear structure that of the 101 known chemical elements the nuclei of the very lightest and again of the very heaviest are less stable than those of medium atomic weights. Thus energy will be released from these heaviest and lightest nuclei in processes that proceed toward more stable nuclei, the reaction moving in opposite directions for the heavy and the light nuclei. Because of these relations of stability the heaviest atoms emit energy when they *split* in fission and thus are greatly reduced in weight, that is, move toward medium atomic weights. On the other hand, the lightest elements emit energy when they are *combined* in fusion, hence also move toward medium atomic weights. Mass disappears in both processes, and reappears as energy of motion or of radiation, the mass of the nuclei after the reaction in each case being less than the mass before the reaction. The basic properties of the two processes have already been shown in Fig. 10, which illustrates how fusion of light nuclei, just like fission of heavy nuclei, releases energy and produces final nuclei lighter than the initial nuclei.

Although the release of energy by fusion has been attained only very recently on earth, it is a process that has always been our most important source of energy, for it is the process that provides the energy radiated by the sun. Deep within the interior of the sun, there exist temperatures of millions of degrees and densities hundreds of times those found on earth. Under these extreme conditions fusion reactions not only are possible but take place with extreme rapidity, and they produce the energy that is radiated to us as light and heat from the sun. On the earth, however, attainable temperatures and densities are much too low for these reactions to take place at an appreciable rate.

The nuclear reactions involved have been known for a long time on earth but they have not produced large amounts of energy. Thus far they have been observed only as reactions of a few bombarding particles, accelerated in cyclotrons or other particle accelerators, rather than in matter at high temperature and density. In our discussion of nuclear reactions in Chapter 2 we have studied the principles that determine the amount of energy released in the nuclear reactions of the light elements. It is extremely easy to compute from these principles how much energy is released in these reactions of fusion. Some of the most common fusion reactions among the very light elements are:

$$\begin{aligned} H^2 + H^2 &\rightarrow He^3 + n + 3.3\ \text{Mev}, \\ H^2 + H^2 &\rightarrow H^1 + H^3 + 4.0\ \text{Mev}, \\ H^2 + H^3 &\rightarrow He^4 + n + 17.6\ \text{Mev}. \end{aligned}$$

This somewhat abbreviated notation is a convenient one for describing these relations; in the first one, for example, two deuterium nuclei fuse to produce He^3 plus a neutron and 3.3 million electron volts of energy. In each case the final products weigh less than the initial reacting nuclei, and it is this difference in weight that, by Einstein's relation, gives the energy release shown with each reaction.

The reactions just listed involve two isotopes of hydrogen but in none of them does the ordinary isotope of hydrogen, H^1, appear as one of the two reacting nuclei. The H^2 is heavy hydrogen, or deuterium, which is present to a very small extent in all ordinary hydrogen. It is manufactured by separation from the much larger amount of H^1 present in ordinary hydrogen. Even though the process is somewhat expensive, at the present time there are many many tons of deuterium available, usually in the form of *heavy water.* Thus there is no question of the availability of deuterium for possible use in the fusion reaction.

The hydrogen isotope of triple weight, H^3, which is called *tritium,* is much more difficult to obtain than deuterium. Even when produced it cannot be kept indefinitely, for, unlike the other two hydrogen isotopes, it is unstable and decays with a half-life of 12 years. However, the reaction involving tritium, the third reaction listed above, shows the excess instability of this isotope because this reaction releases more than four times as much energy as do either of the other two. This reaction also proceeds much more rapidly than the other two and hence is a very useful reaction in the H-bomb, where the energy is released explosively.

It is important to compare carefully the amount of energy released by the reactions of the light elements when fusion takes place with the corresponding amount of energy released when the heavy nuclei undergo fission. At first thought, the amount of energy released by fission, about 200 Mev, seems much larger than the energies listed above for the fusion reactions. However, as we pointed out in Chapter 2, it must be remembered that *per unit weight* the light elements have a large factor in their favor, for each atom of the light elements weighs much less than does uranium, for example. Thus if we compute the amount of energy released *per unit weight* say per pound, of material, and compare the heavy with the light elements, we realize that, far from releasing much less energy than uranium, the light elements actually release as much or more. Taking this difference in weight of the atoms of light and heavy elements into account we find that the reactions listed above release 11 million, 13 million, and 46 million kilowatt hours of energy for each *pound* of material used, as compared to the 11 million kilowatt hours (Chapter 3) released when 1 pound of uranium undergoes fission.

In order to illustrate graphically the manner in which the energy release per pound differs for light and heavy elements, we show in Fig. 45, as a function of atomic weight, the amount of energy obtained per pound for elements of various weights, selecting the particular reactions of high energy yield. It is seen that only for the very lightest and the very heaviest elements do we get appreciable energy, and furthermore that from some of the lightest elements the energy released per pound by fusion is much larger than the fission energy for the heavy elements. The largest energy release per pound in Fig. 45 is for the fusion of two deuterium atoms to form helium,

$$H^2 + H^2 \rightarrow He^4 + 23.7 \text{ Mev},$$

which, although it releases 78 million kilowatt hours per pound, does not proceed rapidly enough to be practical for fusion power. An isotope of lithium, Li^6, is seen to be a possible fusion fuel of great importance, for its reaction with deuterium releases a large amount of energy, and furthermore it proceeds rapidly.

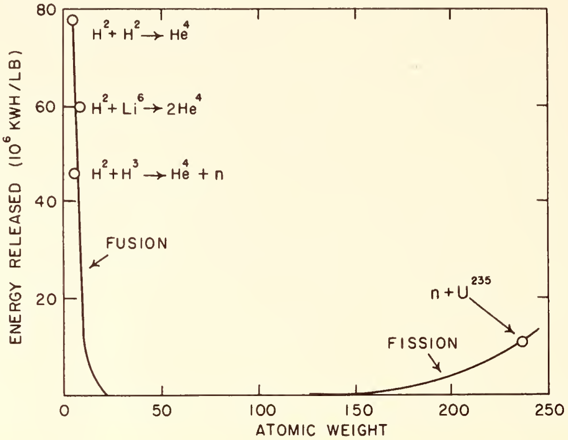


Fig. 45. The amount of energy available per pound of reacting material for different atomic weights. Energy is available for low atomic weights from fusion reactions and at high atomic weights from fission, whereas negligible energy is available for medium atomic weights.

The fundamental difference between fusion and fission reactions, as far as practical attainment of power is concerned, is that it is extremely difficult to get the light elements to react. The interacting nuclei we have listed for fusion reactions all carry electric charges and hence repel each other. Whereas the neutron can enter a uranium nucleus and cause fission even when it is moving extremely slowly, and in fact reacts better the more slowly it moves, the hydrogen nuclei, H^2 and H^3, repel each other strongly and this repulsion must be overcome in some way to cause fusion and release of energy. Of course, if the deuterons or tritons are accelerated in cyclotrons and fired at stationary atoms, now and then one passes close enough to the nucleus of a target atom that a reaction takes place. In this case the accelerated particle is moving fast enough to overcome the electrical repulsion and make fusion possible.

However, the number of atoms involved in the process of acceleration in machines is so small that no practical power can be obtained in this method. It is necessary to get most of the nuclei in the interacting material close enough together to react and there is only one practical way in which to attain this condition—to cause *all* the atoms to move with high velocity. When all the atoms in a given material are moving rapidly and in random directions we say that the material is at high temperature. Actually, if the temperature is sufficiently high, nothing else need be done to promote the fusion reactions. At the extremely high temperature that is necessary, some tens of millions of degrees, the atoms are moving rapidly enough, simply because of the heat motion, that they approach closely enough to each other, in spite of the electrical repulsion, to cause the nuclei to merge and the fusion reactions to take place. When the nuclei are moving sufficiently fast, because of the high temperatures, to cause the fusion reactions to occur, we speak of them as *thermonuclear* reactions, that is, nuclear reactions caused by heat or *thermal* motions of the nuclei.

Once the reaction commences, once some of the atoms approach each other closely enough for their nuclei to fuse, the energy released from the nuclear reactions causes other atoms to be heated still more, they move more rapidly, and the rate of energy release then increases. The process just described is actually the one that occurs in the H-bomb, the only way in which the extreme temperatures necessary have been produced by man. In the bomb, the light elements must be heated to a temperature higher than a million degrees. When the extremely high temperature is attained, however, the thermonuclear reaction starts and the energy released in it causes the temperature to go higher still. This process is a type of chain reaction, as is fission, and, like fission, a tremendous amount of energy is released in an explosive manner, if the reaction proceeds far enough and quickly enough.

The only way yet found to produce the heating necessary to start the reaction is by means of an atomic bomb, in which the energy is produced by fission. If the light elements are incorporated in an ordinary fission bomb, they may be heated to a high enough temperature by the fission explosion that the thermonuclear reactions take place and further energy is rapidly evolved. Thus an H-bomb is manufactured by incorporating the light elements in a conventional A-bomb, whose explosion then acts as a trigger to start the thermonuclear reactions. Because of the large amounts of energy released in the thermonuclear reactions the explosive power of an H-bomb is very much greater than that of an A-bomb, this energy being measured as the equivalent of millions of tons of high explosive instead of thousands of tons as is appropriate for the A-bomb. Of course, causing a thermonuclear reaction to take place by means of the high temperature attained in a A-bomb, and thus having this energy appear as a much greater increase in the energy of the A-bomb, is hardly a practical way to produce energy for peacetime purposes. The whole approach of getting thermonuclear energy in a bomb explosion has really no practical application to peacetime pursuits, if we omit a few unlikely possibilities such as moving mountains and melting polar ice. We shall turn then to the possible ways of getting the energy in a controlled manner rather than as an explosion of unprecedented destructive power.

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The Thermonuclear Reactor

We have just seen why high temperatures are essential for the release of thermonuclear energy in a practical way and also how these temperatures, if obtained in a bomb explosion, release the energy so rapidly that it is difficult to see how it can be used for any practical purpose. There is no way to avoid the necessity of these high temperatures; hence we must face the problem of creating extreme temperatures in a controlled manner rather than by means of an explosion. The energy is released in the sun in a steady way but conditions on the sun differ so greatly from those on the earth, in both temperature and pressure, that a thermonuclear reaction on the sun can proceed in a way that could not be accomplished on the earth. The temperature in the interior of the sun is many millions of degrees, hence all the light elements present are moving sufficiently rapidly that they can merge with each other and react. In addition, the amount of material present per unit volume, that is, the density, is enormously greater than can be attained on earth, and this condition also promotes the energy release by fusion reactions. Since these conditions of temperature and pressure do not hold on the earth, some other principle must be found on which to base the controlled release of the energy of fusion. Moreover, at temperatures over a million degrees all materials would be completely vaporized, hence no container could be built that would hold the reacting elements of a "fusion reactor."

A clue to the method by which the light elements could be contained at a high temperature without exploding is furnished by the fact that at high temperatures their atoms would have their electrons completely removed, that is, they would be completely *ionized.* In other words, they would not be electrically neutral atoms but would be positively charged *ions* with all the atomic electrons removed. Because the ions are electrically charged they can be acted on by magnetic and electric fields, and it is because of the magnetic and electric forces that these fields exert on moving ions that a possible method exists for holding the material together in spite of the high temperature.

A magnetic field makes an ion moving in it follow a curved instead of a straight path. Thus a suitable arrangement of magnetic and electric fields can be envisaged that would keep the rapidly moving particles within a circumscribed region of space without the need of a containing vessel. In the words of Edward Teller, one of the leaders in the development of fusion for power at the present time, the fields act, as it were, as a "magnetic bottle" (Fig. 46). As the particles move in their curved paths they absorb energy from the containing fields, which means that they move faster. This increase in speed amounts to a rise in temperature, which may thus reach the high value—some tens of millions of degrees—necessary for thermonuclear reactions to take place at an appreciable rate. Then, as we have said, the reactions will maintain the required temperature or even raise it higher.

The neutrons produced in the reactions will leave the reacting materials in which the energy is being released, because of their great penetrating power, and will be able to carry energy outside the reaction; this energy can be used as heat in conventional boilers to produce electricity. There is actually a possibility that energy could be obtained from the thermonuclear reactions without going through the rather complicated conversion from nuclear radiation to heat and then into steam and finally to electrical energy. The reason for this extremely favorable possibility is that when the thermonuclear reaction is started the nuclear energy represented by increased motion of ions can be converted into magnetic energy. The magnetic energy can then be drawn off in just the reverse of the process by which energy was fed into the ionized gas to enable it to reach the high temperature in the first place. Thus the coils of wire that surround the reactor and initially produce the magnetic field would act, after the reaction has started, as a generator in which electricity is produced from the energy of motion of the gaseous ions.

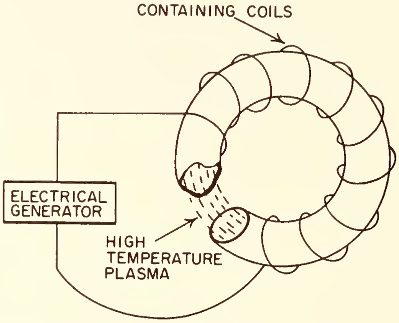

Fig. 46. Schematic diagram of a thermonuclear reactor. The hot plasma is held in place or "contained" by the magnetic field of the coils and the thermonuclear reactions take place in the hot plasma. In an actual reactor the energy generated in the thermonuclear reactions would be carried away by a coolant much as is done in a fission reactor, or possibly in the same coils that produce the containing field.

In this short sketch it is difficult for us to describe the truly formidable obstacles in the way of making such a "magnetic bottle" to hold the energetic ions. The problem is that it is extremely hard to design an arrangement of coils that will produce electric and magnetic fields that will hold or *contain* the gaseous ions without allowing them to escape. The motions of these ions are very complicated and at the present time it is almost impossible to devise an arrangement that will hold the ions in a given volume while the temperature is raised sufficiently to produce the nuclear reactions. Another difficulty arises because it is necessary to have a large amount of gas present in the ionized *plasma,* as the contained ionized gas is called. If the number of contained ions is not great, then it is found that more energy would be used in producing the magnetic fields to contain the ions than will be obtained from the ions by the thermonuclear reactions. Thus the problem is one of designing magnetic fields to hold a large amount of ionized plasma, and to get this plasma to a sufficiently high temperature that the amount of energy given out as nuclear energy is much larger than the amount fed into the machine in the form of magnetic and electric energy.

If such a machine can be designed there are great advantages inherent in it over a uranium-fission reactor for the production of energy. The obvious advantage is that fuel is virtually inexhaustible. If deuterium were to be used for such a thermonuclear reactor, it could be separated rather simply from ordinary water—this being the reason why thermonuclear fuel is often stated to be the entire supply of heavy hydrogen in the ocean. Another advantage is that the extremely complicated chemical problems of reprocessing uranium to remove the fission fragments would not arise in the operation of a thermonuclear reactor. The great range of chemical elements present in the fission fragments are not produced in the simple fusion reactions that we have listed above. Associated with the absence of fission fragments is the greater safety of the machine; an explosion that would release its reacting nuclei would be much less dangerous than an explosion of a uranium reactor, in which tremendous amounts of radioactivity in the form of fission fragments would be spread about the surroundings. The thermonuclear reactor itself would not be free of radioactivity because the structural materials would become intensely radioactive as a result of the large numbers of neutrons that would be produced in it. However, the danger of spreading radioactive debris in case of a catastrophe is not at all of the same order of magnitude as it is for a fission reactor.

The third great advantage of fusion reactors, should they prove feasible, is the possibility just mentioned, that the energy might be converted directly to electricity, the electricity being produced in the same coils that are used to supply the magnetic field that start the thermonuclear reaction in operation. The direct conversion of nuclear to electrical energy would avoid many of the extremely difficult problems associated with fission power reactors, which so far always involve the heat stage. Thus this new method would eliminate all the equipment shown in connection with the power reactors of Chapter 4, namely, the heat exchangers, boilers for developing steam, turbines, and electrical generators.

It is fairly obvious that the difficulties are as great as are the possible advantages of thermonuclear reactors, else they would be in operation at the present time. Rather than speculate at length, however, about the difficulties that might arise in this program, it is perhaps simpler and more accurate to look at what is known of the current status of efforts to attain a successful thermonuclear reactor. Rather extensive efforts are going on in the United States and Russia, so we can look briefly at what is known of the programs of these two countries to see what we can infer about the present activities and the possible success of these efforts.

Soviet Work on Controlled Fusion

It is a well-known fact that the Soviets have carried on a development program on the H-bomb roughly parallel to our own, having exploded their first H-bomb about the same time as ours. However, until recently very little was known in the United States about what the Soviets were doing on the problem of the controlled release of fusion energy. At the time of the Geneva meeting in August 1955 no details of any work on fusion were given by the USSR or the United States. The subject was opened up, as we have already mentioned, to some extent at the Geneva conference, stimulated by the inaugural address of H. Bhabha, the president of the conference. He referred to the release of fusion energy as something that might come in a few years and this rather surprising pronouncement gave rise to much speculation on the part of reporters present.

Because of the insistence of the reporters, a very small amount of information was released at the conference concerning the program of the United States, primarily a bare announcement that work on controlled fusion had been in progress for a number of years and that the effort was expanding. No details were given on the methods that were being followed nor on the probable success, merely a statement that probably many years would elapse before the numerous difficult problems involved in controlled fusion reactors could be solved. At the time of the Geneva meeting the Soviets released no information at all, hence even the small amount of knowledge concerning the United States effort was more significant than the complete ignorance about the Russian program.

This situation—a slight amount of information available on the United States program and none at all on the Russian work—persisted from the time of the Geneva meeting until well into the spring of the following year. The situation was dramatically changed on April 26, 1956, however, when the Russian scientist Igor Kurchatov gave a lecture at the British atomic energy laboratory at Harwell, which revealed in surprising detail the experiments that were being carried out by the Russians on controlled thermonuclear fusion. The amount of detail on the Soviet program released in this talk and later in publications in scientific journals is much more than what the United States has released. Therefore we are describing the Soviet work first in the present book simply because in this way we have so much more technical detail available on which to base our explanation of the principles of fusion power. It would be difficult to describe the methods being developed if we were to base the description on declassified United States information, for only the most general descriptions of the techniques have been made available so far in this country.

Because of the unprecedented nature of the lecture given by Igor Kurchatov at Harwell, a few preliminary remarks are in order. It was a typical high-level technical talk, honest and straightforward, and not an attempt to convey the impression of releasing information without really doing so. Many detailed numerical values were given in connection with the experiments described and this detail would not be necessary if the desire were simply to create a certain impression. Actually, the talk was very much like those given by the Russians at the Geneva meeting the previous summer. At that time, the American scientists had many opportunities to talk to their Soviet counterparts and the detailed exchanges were convincing evidence that they were not holding back information in the fields under discussion. Kurchatov's talk on the controlled thermonuclear reaction was just the same type of lecture and leads to the conclusion that in this particular field of fusion, as in the neutron work at Geneva, the Soviets are releasing the great bulk of their basic work. It is interesting that Kurchatov gave another talk at Harwell, on liquid-moderated power reactors, and this talk was again a straightforward one with a wealth of technical detail.

It is of particular importance that the fusion report represents the first time that the Soviets have released information ahead of us. In the past their releases have always followed ours, but in this case they have jumped very far ahead of us in releasing details of the thermonuclear experiments. This piece of information has little to do with our relative positions as far as technical accomplishments in the field are concerned; this latter matter is difficult to discuss because of the high classification status of our own work.

Kurchatov began by describing the fundamental problem of the attainment of power from the thermonuclear reaction—the containment of a gaseous plasma at a temperature of the order of several million degrees. He explained that the high temperature is necessary so that the ions of the plasma, for example, deuterons or tritons, may move sufficiently fast to overcome the electrical repulsion between them and produce the nuclear reactions in which energy is released. At such extremely high temperatures no ordinary methods of containment are practical and resort must be made to electromagnetic fields for keeping the ionized gas from escaping. For practical results, the entire mass of material must be raised to the high temperature rather than a small fraction of it. If the ionized plasma in a gas discharge could be held together steadily as energy is fed into it, then the temperature would rise sufficiently high that nuclear reactions would begin to take place and energy would be evolved. However, such a static arrangement, Kurchatov explained, is inherently unstable and the Russians turned early in their program to the use of pulsed discharges. The electromagnetic forces in a pulsed discharge are such as to cause the discharge to contract to a very fine line and this *"pinch effect"* causes a rapid rise in temperature in the condensed column. Soviet scientists studied this compressed gaseous discharge in a number of gases, using moderately high voltage but extremely heavy currents.

Electrical energy stored in large *condensers* was passed through cylinders containing the gas under study, usually deuterium, as shown schematically in Fig. 47. The discharge tubes varied from several inches to several feet in diameter and up to 6 feet in length. The current pulses passed through these tubes ranged up to 2 million amperes and instantaneous power rates were as high as 40 million kilowatts. In the discharge the heavy currents attract each other strongly and the discharge thus shrinks rapidly to a thin line, the pinch effect, in which the concentration of current causes a rapid rise in temperature. The concentrated discharge then breaks, in a thousandth of a second or so, into an irregular shape because of its instability. After the break of the pinch rather complicated electric currents develop in the tube because of the great turbulence of the plasma, at times currents actually existing in the reverse direction.

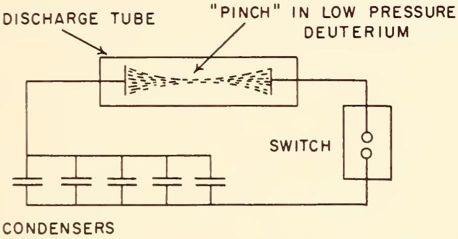

Fig. 47. The apparatus used by the Soviet scientists to study thermonuclear reactions in a pulsed discharge; as the electric discharge shrinks to a line in the pinch effect, the temperature rises rapidly and nuclear reactions are produced. No true thermonuclear effects have been obseved as yet with this equipment, however.

The test of the attainment of high temperatures in the momentary pinch is the production of an appreciable number of nuclear reactions, of the types we have listed earlier in this chapter. According to Kurchatov, as early as 1952 Soviet scientists found rather high-energy x-rays and neutrons emerging from the pinch. These radiations, particularly the neutrons, indicated quite definitely that nuclear reactions were taking place in the gaseous discharge. The scientists at first thought that they had reached the high temperatures, of the order of several million degrees, necessary to produce nuclear reactions. However, extensive tests showed that the temperature could not be high enough to make a significant number of nuclear reactions at the currents used in the experiments.

Another difficulty in explaining the Soviet results was that x-rays of energies as high as 300,000 volts were emitted by the tube even when the voltage across the discharge was as low as 10,000 volts. A number of careful tests showed that the velocity of the deuterons and electrons in the tube was very high, as would be necessary to explain the reactions, but that these velocities were not a result of high temperature. Rather the velocities were produced by local high electric fields that somehow were a result of the extreme instability of the pinch as it collapsed. These high electric fields could accelerate deuterons to a sufficient energy that they could make nuclear reactions, primarily the first reaction we have listed earlier,

$$H^2 + H^2 \rightarrow He^3 + n + 3.3 \text{ Mev},$$

in which neutrons of about 2 Mev energy are emitted, the He^3 carrying away the balance of the 3.3 Mev produced.

The neutrons found by the Soviet scientists were *not* produced by a true thermonuclear effect, for they result from the ordered motion of only a small fraction of the ions in the discharge tube. This is a very different situation from a true thermonuclear reaction in which *all* of the material would be heated to a sufficiently high temperature that the nuclear reactions could take place, and large amounts of energy would be produced. Thus, whereas the Soviet scientists no doubt produced nuclear fusion reactions in their discharge tubes, they did not produce the high temperatures that would be necessary for true thermonuclear reactions. In order to make a real thermonuclear reaction and to produce power in an economical way it is necessary to reach a true high temperature, that is, to have all the ions in the gas moving at high speed. The *ordered* motion produced by the local momentary high electric fields in the Soviet experiments is not a true temperature, which is associated with *disordered* motion.

Another fundamental difficulty of the approach in which a pulsed discharge is used is that the nuclear reactions take place for only a very short period of time, no power being produced while the condensers are being recharged in readiness for the next pulse of current. However, because of the inherent instability of a pinched plasma it would seem very difficult to produce some steady type of discharge at a very high temperature in the Soviet type of discharge tube. Judging from the Soviet results, even the use of pulsed discharge has enough difficulty that as yet no true temperatures in the thermonuclear region have been attained.

The Kurchatov lecture, containing a large amount of practical detail about the Soviet experiments, serves to emphasize the great technical difficulty of the practical attainment of thermonuclear power. To use a chemical analogy, we would certainly say the work is still at the "test-tube stage" and not at all at the "pilot-plant" or "semiworks" level at present. Even when true thermonuclear reactions are produced, the problem still remains of getting sufficient power from the reaction, probably in the first models as heat, to make up for the large amounts of power that must be supplied to furnish the containing electromagnetic fields. Also, although no highly radioactive fission products are left, as is the case with a normal chain reaction, the very penetrating high-energy neutrons that are produced will necessitate extremely thick shielding. In addition, the radiation damage of these high-energy neutrons to the materials of the thermonuclear reactor itself will be serious indeed. It is clear that the Soviet efforts so far are devoted to the production on a laboratory scale of the extremely high temperature necessary to produce nuclear reactions. They are not yet, judging from Kurchatov's statements, at the stage where the later practical problems of production of economical power from fusing nuclei have been faced.

Some months after the Kurchatov talk, several detailed articles appeared in the Russian technical journal, *Atomic Energy,* articles that were not generally available in the United States for several additional months because of the time involved in translating them into English. These articles, however, have now appeared in the United States in translated form and strongly support the impression created by the Kurchatov lecture that the Soviets have a large thermonuclear-power program and that they are publishing the technical details freely. The articles repeat the conclusions given by Kurchatov but include much more of the numerical data and details of the experiments involved. The detailed material certainly completely justifies the view that the work described by Kurchatov was actually performed by the Soviets and was not merely propaganda, or bait to induce us to reveal our information without gaining anything in return.

The United States Fusion Program

A few months after the Geneva meeting some additional information of a general nature was released about the United States fusion program. This information revealed that research was being pursued at several locations, primarily at Princeton University, Los Alamos Laboratory, and Livermore Laboratory, with additional work at several other research centers. The official release also stated in general that the research involved electromagnetic methods for containing plasma while its temperature was raised sufficiently for thermonuclear reactions to take place.

Rough descriptions of some of the machines for attaining this objective were given, although the details were of an extremely sketchy nature; the probability of success in the near future was not apparently very high, judging from the name of one of these machines, the "Perhapsatron." No information was revealed at the time as to whether plasma had been raised to sufficiently high temperatures that true thermonuclear reactions could take place. Thus it was not known publicly whether we had reached or passed the stage at which the Soviets were at the time of the Kurchatov lecture.

Early in June 1956 a conference was held at the Oak Ridge National Laboratory on the controlled thermonuclear process at which scientists were present from all the major laboratories in the United States, not only from those laboratories working directly on the thermonuclear process. It was shortly after this "Sherwood" meeting, Sherwood being the name given by the AEC to the controlled-fusion program, that a definite release on the part of the United States Atomic Energy Commission was made.

This release was contained in a speech given by Dr. Edward Teller of the Livermore Laboratory at a meeting of the American Nuclear Society in Chicago on June 8, 1956, immediately after the Sherwood meeting in Tennessee. Actually, little information was revealed in Teller's talk on the status, magnitude, or chances of success of the program in the United States. The talk was devoted primarily to a discussion of the mathematics, in a simplified form, of the computation of the temperature required for appreciable thermonuclear reactions to take place and power to be produced. Teller also discussed the way in which the hot plasma would lose energy by radiation at the high temperatures. It is of course necessary to have energy generated by the thermonuclear reactions at a rate higher than that at which it is lost by radiation, if the temperature in the machine is to be high enough to permit the extraction of energy from it for production of useful power.

As far as the actual practical problem of confining a highly ionized plasma was concerned, the discussion was extremely brief and limited merely to several broad statements that the confinement would probably be a matter of properly shaped magnetic fields. Some description was given of the nature of the instability of contained plasma that would cause it to break away and escape from its containing field. It was intimated that these instabilities are rather serious and would require much additional work before the magnetic fields could be made to contain plasma successfully.

Teller described these difficulties by comparing them to the problem of designing airplanes. He mentioned that in constructing an airplane people could argue that "after all, birds fly," but there is no corresponding analogy in the case of developing a thermonuclear reactor. Presumably he did not consider the sun a sufficiently close analogy, because of the tremendous differences in temperature and density of the sun relative to conditions on the earth. He did describe several advantages of themonuclear power should it be possible to develop it at some future time, advantages that we have described earlier in the present chapter.

As far as the chances of ultimate success are concerned and the time scale involved, Teller said that the confinement of the plasma can probably be accomplished, "although it appears to be perhaps decades in the future." This opinion, by a man who is probably the foremost expert in the field, shows without a doubt that the competition from thermonuclear power is hardly such a serious matter that it should change the fission program of a country, or the design of particular fission reactors, because of the possibility that thermonuclear power might make them obsolete. It was this latter view that was expressed by unknowing science writers at

Geneva, that perhaps we should not put too much effort into fission because fusion was just around the corner, that unfortunately led to a large amount of confusion for a short period of time at the conference.

The Place of Fusion in the Atomic-Energy Program

Since the time of the Geneva meeting, when the possibility of controlled fusion was brought to the attention of the public so forcibly by Bhabha's speech, there has been continuing interest and, of course, some conflict concerning the proper place of fusion in our atomic-energy program. It is useful to examine the divergence in views on this subject, for it illustrates very well many of the conflicting forces that must be harmonized in fostering the goods of atomic energy without harming our national security.

As is true of fission, the uses of fusion for peace and for war are extremely closely intermingled; for example, developments that will lead to practical use of fusion power are also useful in designing more efficient H-bombs. The same nuclear reactions that are used in one are essential to the other. However, beyond these basic similarities, there are great differences as well. Thermonuclear reactors *are* essentially different from H-bombs in all the technical details of construction; hence it is possible to argue that the field of controlled-fusion power can be kept completely open while that of H-bombs remains classified.

There is actually much validity to the latter point of view, for the technical devices used in the thermonuclear reactor, whose development constitutes the main problem in the attainment of economical fusion power, have no connection with the problems of exploding H-bombs, for which there is no containment of ionized plasma. The method of detonating H-bombs, that is, the matter of getting an extremely high temperature in a short time, is fundamentally different from the containment of the plasma. Thus it actually is true that much of the detailed development of H-bombs can be kept secret while the methods of attainment of controlled fusion are opened up completely.

However, the whole question is unfortunately much more complicated: even if agreement is reached on the technical separation of H-bombs and fusion reactors it is still possible to consider that *both* should be kept secret. The reason for this is simply that successful controlled fusion would supply almost inexhaustible amounts of cheap energy and such production of energy is an essential part of our war potential. It is thus necessary to look into the deeper aspects—not merely the question of whether fusion has only a direct military application.

The problem is one of where the line should be drawn on releasing information, even though it is clear that such information does give some aid to potential enemies. This aid, however small it might be, must be balanced off by the accelerating effect of the release on our own program if we are to conclude that such release is to be justified. A most thoughtful discussion of the principles involved, and with particular reference to the fusion program, was made by the McKinney panel on industrial atomic energy, which published its report in January 1956. The conclusion of the McKinney panel was that the principle already established in connection with fission energy, namely, that production of electric power for peacetime purposes only should be completely opened up and that the manufacture of bombs only should be kept secret, could be applied equally well to fusion. The position of the McKinney panel was plain—that the whole field of the production of power from the controlled fusion reaction should be thrown completely open. The field of H-bomb development should be kept closed, but it was felt that the gain to our own society, the stimulating effect to our progress, was so great that the danger of revelation of our program to possible enemies would be obviated by the great advantages.

An interesting point brought out by the McKinney report is that there is another reason for release of information that goes beyond the consideration of the general aid to scientific progress versus the aid to our potential enemies. This additional consideration has to do simply with the matter of business and the placement of investment capital in our industrial system. The report brought out the fact that it is actually inconsistent for the government to attempt to persuade private industry to invest capital in the development of atomic energy, and at the same time to withhold information on the possibilities of fusion as a source of power.

Thus it was pointed out that companies are extremely unlikely to put large amounts of capital into development plants producing power by fission if there is any chance that in a few years these plants may be made obsolete by fusion power. Of course, to those people who have read the small amount of material that has been published on fusion, especially if they have read carefully between the lines, it becomes obvious, as we have mentioned, that fusion is not going to compete with fission for many decades to come. However, as these facts have not been clearly spelled out, they perhaps do not reach all the people who need to know them, and thus there might well be understandable reluctance to support development of fission reactors to the fullest possible extent.

The conclusion is thus that more of the United States thermonuclear program for peacetime power could be opened up, and that the increased rate of progress in the field would more than offset the disadvantage that would accrue from revealing the status of our program to the rest of the world. If the rest of the world were much behind us, then perhaps it could be argued that we should not reveal our own program, because it would advance the programs of other nations tremendously. However, even though the real status of our program is still classified, sufficient information has been released to make it fairly easy to estimate that we are not ahead of the Russians, or the British for that matter, by an extremely large margin. It thus seems clear that the best way to keep ahead in a field where things are reasonably close at the present time is to open the field just as much as possible. Then the benefit of criticism of all scientists, the rapid advances that are made when discoveries are immediately brought into the light of day, will take place in the fusion field as in any other open branch of science. In this connection it is extremely encouraging that two companies in the United States, General Electric and General Dynamics, have started their own fusion research programs.

However, we must also remember that there are arguments on the other side and that it is simply not possible to open things completely without careful consideration of all factors on both sides, and as careful a weighing of these factors as can possibly be done. This kind of weighing of the evidence is now going on in the United States and the fact that some releases have come in the last few months of 1956 makes it seem clear that probably more information yet will be released, and that the thermonuclear program can be speeded up greatly, when things are brought into the normal, free interplay characteristic of scientific progress.

GLOSSARY

GLOSSARY

The technical terms important in the field of atomic energy are listed here, together with brief explanations of their meanings.

A-bomb. The bomb in which energy is released by the fission of a heavy element; it is also used to trigger an H-bomb.

Alpha particles. The nuclei of helium atoms, each consisting of 2 protons and 2 neutrons. Alpha particles are emitted from certain radioisotopes, particularly the heavy nuclei such as radium.

Atom. The smallest particle into which matter may be divided without losing its characteristic properties; an atom is made up of a very small massive nucleus, surrounded by electrons.

Atomic number. The number of protons in a nucleus, being numerically equal to the electric charge on the nucleus because each proton has unit positive charge. As the entire atom is electrically neutral, the electrons surrounding the nucleus are equal in number to the protons.

Atomic weight. The weight of an atom expressed in terms of the number of neutrons and protons contained in the nucleus. Thus beryllium, which has an atomic weight slightly greater than 9, contains 5 neutrons and 4 protons. The weight is not exactly an integer because of the equivalence of mass and energy.

Barn. The unit in which cross sections of nuclei are measured; it is equal to 10^{-24} cm^2 (decimal point followed by 23 zeros and a one).

Beryllium. The element of atomic number 4 and atomic weight 9, its nuclei each containing 5 neutrons and 4 protons; it is very useful as a neutron moderator because of its low absorption.

Beta particles. Fast-moving electrons, emitted from most radioisotopes.

Blanket. The layer of an element, such as U^{238} or thorium, in a breeder or converter reactor in which fissionable material is produced by neutron capture. From U^{238} and thorium, U^{233} and Pu^{239} result eventually, after two beta particles are emitted in each case.

Boiling-water reactor. A reactor in which water is allowed to boil directly inside the reactor itself, thus producing steam without the usual intermediate step of transferring the heat from a coolant to a boiler in which steam is made.

Breeding. The process in which more fissionable material is made in a reactor than is consumed as fuel; strictly speaking, the term should be applied only when the same material is produced as is consumed in the reactor, for example, U^{233}, which can serve as fuel and also be produced in a layer of thorium surrounding the reactor.

Carbon. The element of atomic number 6 and atomic weight 12, its nuclei each containing 6 neutrons and 6 protons; in the form of graphite it is very useful as a neutron moderator for it slows neutrons without absorbing them appreciably.

Chain reaction. The process in which fission is propagated from nucleus to nucleus in a fissionable isotope, such as U^{235} or Pu^{239}, by means of the neutrons emitted during fission. The chain reaction increases rapidly in intensity, for example, in the A-bomb, unless controlled, as in a nuclear reactor.

Chemical reaction. The interaction of various atoms in which the arrangement of the electrons surrounding the nuclei is changed but not the nuclei themselves.

Compound. A material consisting of a union of two or more elements in a fixed ratio by weight. An example of a compound is water, consisting of hydrogen and oxygen in a two-to-one ratio, symbolized as H_2O.

Control rod. A metal rod, usually containing boron, that is used to control the intensity of the chain reaction in a reactor by means of its absorption of neutrons.

Conversion. The process in which a fissionable material is made by neutron capture while another is being consumed inside the reactor, as plutonium in a uranium-fueled reactor; the term is usually applied when the amount of fissionable material thus made is less than the amount consumed.

Coolant. The material used in a nuclear reactor to remove the heat energy resulting from fission. In a power reactor, this heat energy is used to generate electrical power.

Critical size. The amount of fissionable material that is just large enough to sustain the chain reaction.

Cross section. The quantity that expresses the strength of interaction between a nucleus and neutrons; the larger the cross section the more likely the nucleus is to absorb the neutron, thus causing a nuclear reaction.

Curie. An amount of a radioisotope that emits radiation at the same rate as 1 gram of radium.

Deuterium. The isotope of hydrogen of atomic weight 2; its nuclei each contain 1 neutron and 1 proton.

Einstein's equation. The formula that is used to calculate the amount of energy E that is released when a certain amount of matter m disappears: $E = mc^2$, where c is the velocity of light.

Element. A material consisting of one kind of atom only; 101 elements are now known, extending from hydrogen, the lightest, to mendelevium, the heaviest.

Electron. The smallest unit of negative electricity; the electron has a mass much smaller than that of atomic nuclei and an electric charge equal in magnitude to that of the proton but of opposite sign.

Electron volt. The unit in which energies are measured in nuclear physics, abbreviated ev. It is the energy gained by one electron when it is acted on by a potential difference of 1 volt. The energies of nuclear reactions are often expressed in millions of electron volts, abbreviated Mev.

Excess reactivity. The amount by which the neutrons of one generation exceed those of the previous generation in a reactor. If the excess reactivity is large the intensity of the chain reaction will increase rapidly with time.

Exponential function. The mathematical function that describes the process in which a quantity is multiplied by the same number repeatedly. This function describes the growth of money by means of compound interest or of the number of neutrons in a chain reaction.

Fallout. The radioactive material resulting from a bomb explosion that continues to be deposited on the earth's surface for a long time after the explosion.

Fission. The splitting of a heavy nucleus, for example, U^{235} or Pu^{239}, after absorption of a neutron. In the splitting a large amount of energy is released, and two fission fragments plus several neutrons are produced.

Fission fragments. The two parts, approximately equal in weight, into which the uranium or plutonium atom splits in the process of fission; they are usually highly radioactive, disintegrating several times before reaching stability.

Fuel rod. The form in which uranium fuel usually exists in a reactor. It is in the form of metal rods, covered with a protective coating to prevent the escape of dangerous fission fragments.

Fusion. The nuclear reaction in which light elements, necessarily rapidly moving, are combined, large amounts of energy being released in the process.

Gamma rays. Short-wavelength radiation, similar to x-rays but of greater energy; gamma rays are emitted by almost all radioactive nuclei.

Geiger counter. The instrument that is used to detect the radiations (alpha, beta, or gamma) emitted by radioisotopes; it is extremely valuable in experiments with tracers because it can respond to the passage of a single ray.

Generation (of neutrons). The neutrons in existence at a particular instant in a nuclear reactor; these neutrons cause fission with the emission of more neutrons, which constitute the next generation.

Genetic effects of radiation. The changes in future generations of plants or animals produced by radiation of individuals of the present generation. The changes, usually deleterious, are caused by mutations of the genes in the germ cells.

Graphite. The chemical element carbon in a particular atomic arrangement. Graphite is a soft, black material useful as a neutron moderator. Diamond is also carbon, but of a different atomic arrangement.

Half-life. The length of time required for half of the atoms of a radioisotope to disintegrate. This type of disintegration with a characteristic half-life gives rise to an exponential form for the decay of the radioisotope.

H-bomb. The bomb in which fusion takes place after the light elements present are heated by the explosion of an A-bomb.

Heavy water. The variety of water containing heavy hydrogen (deuterium) combined with oxygen. Its formula is D_2O, as H_2O is that of ordinary or light water.

Homogeneous reactor. One in which the uranium fuel is mixed with a liquid moderator, which can be light or heavy water or a molten metal, instead of being formed into metallic rods.

Ion. An atom in which some of the electrons surrounding the nucleus have been removed, or extra ones added. As the original atom is electrically neutral, the ion is charged positively or negatively.

Isotopes. Atoms of a given chemical element with different weights; isotopes of an element thus have the same number of protons in their nuclei but different numbers of neutrons.

Kilowatt. The usual unit of electrical power, being equal to 1000 watts. A common size of lamp bulb consumes 100 watts or 0.01 kilowatt; a large reactor may operate at 200,000 kilowatts.

Kilowatt-hour. The usual unit of electrical energy. It is the amount of energy consumed when 1 kilowatt is used for 1 hour.

Lattice. The structure of the central part of a nuclear reactor, usually consisting of uranium fuel rods held in a moderator such as graphite.

Leakage. The escape of neutrons from a chain-reacting material; if the leakage is too large the chain reaction cannot proceed.

Moderator. The material that is used in a nuclear reactor to slow the neutrons by repeated collisions so that they are more likely to produce fission in the uranium fuel.

Molecule. The smallest unit into which a compound can be divided without losing its characteristic properties; a molecule is made up of several unlike atoms, arranged in a specific pattern.

Mutations. The changes in genes of the germ cells that affect characteristics of offspring; the mutations may be spontaneous or caused by various agents, such as radiation.

Neutron. One of the two constituents of nuclei, being distinguished from the proton by its lack of electric charge, but having the same mass as the proton.

Neutron-capture therapy. The method of treating brain tumors by injecting boron, then placing the head of the patient in an intense beam of slow neutrons.

Neutron diffraction. The study of the structure of crystalline materials by the scattering of neutrons; it is very closely analogous to the study of crystals with x-rays, which has been in use for many years.

Neutron lifetime. The length of time between the formation of a neutron in a reactor and its disappearance, which may occur in various ways; the neutron lifetime is very short, typically about 0.001 second.

Neutron mirror. A highly polished surface that can reflect a neutron beam when it is incident at a very small or "grazing" angle.

Nuclear reaction. The interaction of several nuclei involving a transformation in which different nuclei result. The energy changes in a nuclear reaction are usually about a million times as large as those in a chemical reaction, such as the burning of coal.

Nucleus. The massive central part of an atom, consisting of neutrons and protons, and having a positive electric charge. An atom consists of a nucleus surrounded by electrons, in number equal to the protons in the nucleus.

Pile. The name at first commonly used for the nuclear reactor. Its origin is based on the fact that the first reactor was constructed by "piling" blocks of graphite and lumps of uranium in a regular geometric arrangement.

Pinch effect. A method by which plasma is heated to a very high temperature by means of a sudden discharge of electricity; this is a possible method for producing high temperatures and thermonuclear reactions.

Plasma. A collection of ions, which, if consisting of light-weight atoms and at sufficiently high temperature, can produce thermonuclear reactions.

Plutonium. The chemical element of atomic number 94. Its isotope Pu^{239}, which is made in nuclear reactors, is highly fissionable and very similar in behavior to U^{235}. It is a bomb material and potentially useful as a reactor fuel.

Proton. One of the constituents of nuclei, having one unit of positive electric charge and a mass equal to that of the neutron.

Radiation sterilization. The sterilization of food by subjecting it to intense irradiation with alpha, beta, or gamma rays, or neutrons.

Radioactivity. The emission of various types of radiation—alpha, beta, or gamma—by nuclei that are unstable. The emission of energy as radiation is the mechanism by which the unstable radioisotopes change to stable nuclei.

Radioisotopes. Nuclei that have been made radioactive, for example, by being placed inside a nuclear reactor. They are unstable and emit their energy as alpha, beta, or gamma rays.

Radium. The chemical element discovered by the Curies that has been widely used for treatment of disease because of its emission of alpha rays.

Reactor. A structure in which the controlled chain reaction is operated; it usually contains a coolant for removing the heat produced in fission and is surrounded by a protective shield.

Reflector. The moderator that surrounds the central lattice of the reactor; its purpose is to scatter neutrons back into the reactor and thus decrease the number leaking from it.

Reproduction factor. The ratio of the number of neutrons in a reactor to the number of neutrons in the preceding generation; if the reproduction factor is greater than 1 the chain reaction will increase in intensity.

Resonance. The unusually high probability for absorption of a neutron by a nucleus when the energy of the neutron has exactly the right value; these resonances are observed as sharp peaks in the measured curves of cross section for different neutron energies.

Roentgen. The unit of radiation exposure; the unit usually used for expressing amounts of radiation received is the milliroentgen, which is 0.001 roentgen.

Shield. The massive wall, usually of concrete combined with iron, for stopping the dangerous radiations from a nuclear reactor.

Spontaneous fission. The splitting of uranium or plutonium that occurs once in a great while even when the nuclei do not absorb neutrons.

Strontium. An element whose radioactive form, radiostrontium, is produced in fission and hence is present in "fallout" from atomic-bomb explosions. It is particularly dangerous because it deposits in bone if ingested and can lead to bone cancer.

Swimming-pool reactor. A nuclear reactor consisting of a lattice that is lowered into a large pool of water, which constitutes the shield.

Thermonuclear reaction. The reaction of fusion of light nuclei in which the nuclei are caused to combine by means of their high velocity, produced by extreme temperature.

Thermonuclear reactor. A machine in which a plasma of ions is held, for example, by magnetic fields. If the temperature of the plasma is extremely high, thermonuclear reactions take place, producing power.

Tracer. A radioisotope used to reveal, by means of its emitted radiations, the location of a particular chemical element in some process under study.

Tritium. The isotope of hydrogen of atomic weight 3; its nuclei each contain 1 proton and 2 neutrons.

Uranium. The heaviest naturally occurring atom; its two principle isotopes, U^{235} and U^{238}, differ greatly in their nuclear behavior, the first fissioning readily with slow neutrons, the second only with very fast neutrons.

Wavelength of neutrons. The length of the wave associated with a neutron; for very slow neutrons the wave properties are predominant because the wavelength increases as the neutron velocity decreases, whereas fast neutrons, of short wavelength, resemble particles in their behavior.

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